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Commercial Implementation of Ultrasonic Velocity Imaging Methods via Cooperative Agreement Between NASA Lewis Research Center and Sonix, Inc.

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COMMERCIAL IMPLEMENTATION OF ULTRASONIC VELOCITY IMAGING METHODS VIA COOPERATIVE AGREEMENT BETWEEN NASA LEWIS RESEARCH CENTER AND SONIX, INC.

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ABSTRACT

This article describes the commercial implementation of ultrasonic velocity imaging methods developed and refined at NASA - Lewis Research Center on the Sonix c-scan inspection system. Two velocity imaging methods were implemented: thickness-based and thickness-independent reflector plate methods. The article demonstrates capabilities of the commercial implementation and gives the detailed operating procedures required for Sonix customers to achieve optimum velocity imaging results. This commercial implementation of velocity imaging provides a 100x speed increase in scanning and processing over the lab-based methods developed at Lewis. The significance of this cooperative effort is that the aerospace and other materials development-intensive industries which use extensive ultrasonic inspection for process control and failure analysis will now have an alternative, highly accurate imaging method commercially available.

INTRODUCTION

Automated ultrasonic velocity imaging was developed in 1986 at NASA Lewis Research Center in response to the need for more precise and accurate nondestructive evaluation (NDE) methods to characterize the high performance structural ceramic materials under development at the time (ref. 1). Velocity images were practically unattainable prior to the automated developments at NASA; early attempts at velocity "mapping" were performed at random sample locations or by line scan (refs. 2 and 3). In the latter experiments, velocity measurements were performed only at a small number of selected sample locations to compare the material quality or elastic constants in those areas (ref. 4). Ultrasonic velocity imaging has proven to be significantly more sensitive to microstructural (Eg. pore fraction, density) gradients than images derived from high-resolution ultrasonic scanning that maps peak echo amplitude (c-scanning) (ref. 5). This appears to be especially true in the case of monolithic, fine-grained ceramics that exhibit very little ultrasonic attenuation below 100 MHz. Since the high-performance monolithic ceramic market is estimated to be significant by the year 2000 (ref. 6), velocity imaging may be vital as a quality control tool for these ceramics. The additional advantage of velocity imaging over c-scanning is that microstructural variation is shown *quantitatively in terms of an actual ultrasonic wave propagation parameter* scaled to gray/color scale rather than just a gray/color scale associated with mapping peak echo heights.

A weakness of conventional ultrasonic velocity imaging, and ultrasonic imaging in general, is that the image shows the effects of thickness as well as microstructural variations unless the part is uniformly thick. To address this issue initially, NASA applied an error analysis methodology that allows one to define the percent velocity variation due to each of thickness and microstructural variation in a velocity image (ref. 7). This allowed one to conclude whether the percent variation seen in the velocity image was due to thickness variation, microstructural variation, or a combination of the two. However, this methodology allowed only a global generalization and the image itself could not be changed as a result of this methodology. A major step forward in velocity imaging occurred in 1994 when NASA extended the single point measurement methodology of refs. 8 and 9 to *eliminate* the effects of thickness variation from the velocity image so that the velocity variation seen in the image is solely due to microstructural variation (ref. 10).

Present commercially-available immersion ultrasonic c-scan systems have increased in capability due to the dramatic increase in computer power (Eg. scan speed, processing speed, disk space) over the last 10 years. This allows for sophisticated ultrasonic techniques previously available only as laboratory tools to be incorporated into the present commercially-available ultrasonic systems. One company currently manufacturing state-of-the-art ultrasonic scan systems is Sonix, Inc. of Springfield, Virginia. Their systems are used worldwide for microelectronics, materials research, failure analysis and other NDE. Sonix is a small business with 40 employees that was formed in 1987 and has experienced rapid growth in sales since its inception. In 1993, Sonix won the U.S. Department of Commerce "Excel-lence in Exporting" award. NASA - Lewis chose to work with Sonix for two main reasons: (1) because Sonix is an innovative leader in ultrasonic imaging systems and (2) because the results would be cost-effective for NASA as NASA already owned a Sonix c-scan inspection system. NASA also felt that transferring the technology quickly to increase an American company's global competitiveness was of high priority. From Sonix's perspective, they recognized the market potential of the NASA-developed methods for ultrasonic assessment of material quality.

On January 3, 1995, Sonix and NASA began a shared-cost cooperative agreement (NCC3-385) for the purpose of having Sonix incorporate into their c-scan systems ultrasonic velocity imaging methods developed at NASA's Lewis Research Center. The Sonix implementation of Lewis-developed methods has been beta-tested at both Sonix and Lewis and will be available for worldwide commercial distribution ~4/96. NASA has made several further suggestions to increase user-friendliness of the system but in general, the implementation is working beyond original expectations. This article demonstrates capabilities of the commercial implementation and gives the detailed operating procedures required for Sonix customers to achieve optimum velocity imaging results. Results are shown for monolithic ceramics and polymer matrix composite materials.

BASIC METHODS

Velocity measurements are generally made in the pulse-echo mode with a transducer either contacting the sample (contact mode) or separated by a liquid coupling path (immersion mode). Figure 1(a) shows a schematic of the pulse-echo testing and resulting waveforms for immersion testing. The time delay in the pulse-echo mode (2τ) between 2 successive back surface echoes (fig. 1(b)) is determined and velocity (V) is calculated from:

$$V = \frac{(2d)}{(2\tau)} \tag{1}$$

where 2d is twice the sample thickness. This method is heretofore referred to as the thickness-based velocity method. The advantage of this method is that it provides a very precise image and is relatively simple to implement. The disadvantage is that, since only one thickness value is used in the velocity image calculation, the resulting image shows a combination of thickness and microstructural variation effects unless the part is of very uniform thickness (± 5 µm).

Another pulse-echo method for measuring velocity requires positioning a plate behind the sample and separated from the sample by an additional fluid path (refs. 8 and 9) (fig. 1(c)). As before, the time-of-flight of successive echoes off the sample back surface is recorded as is the time-of-flight off the reflector plate with and without the sample present. Velocity is then determined from:
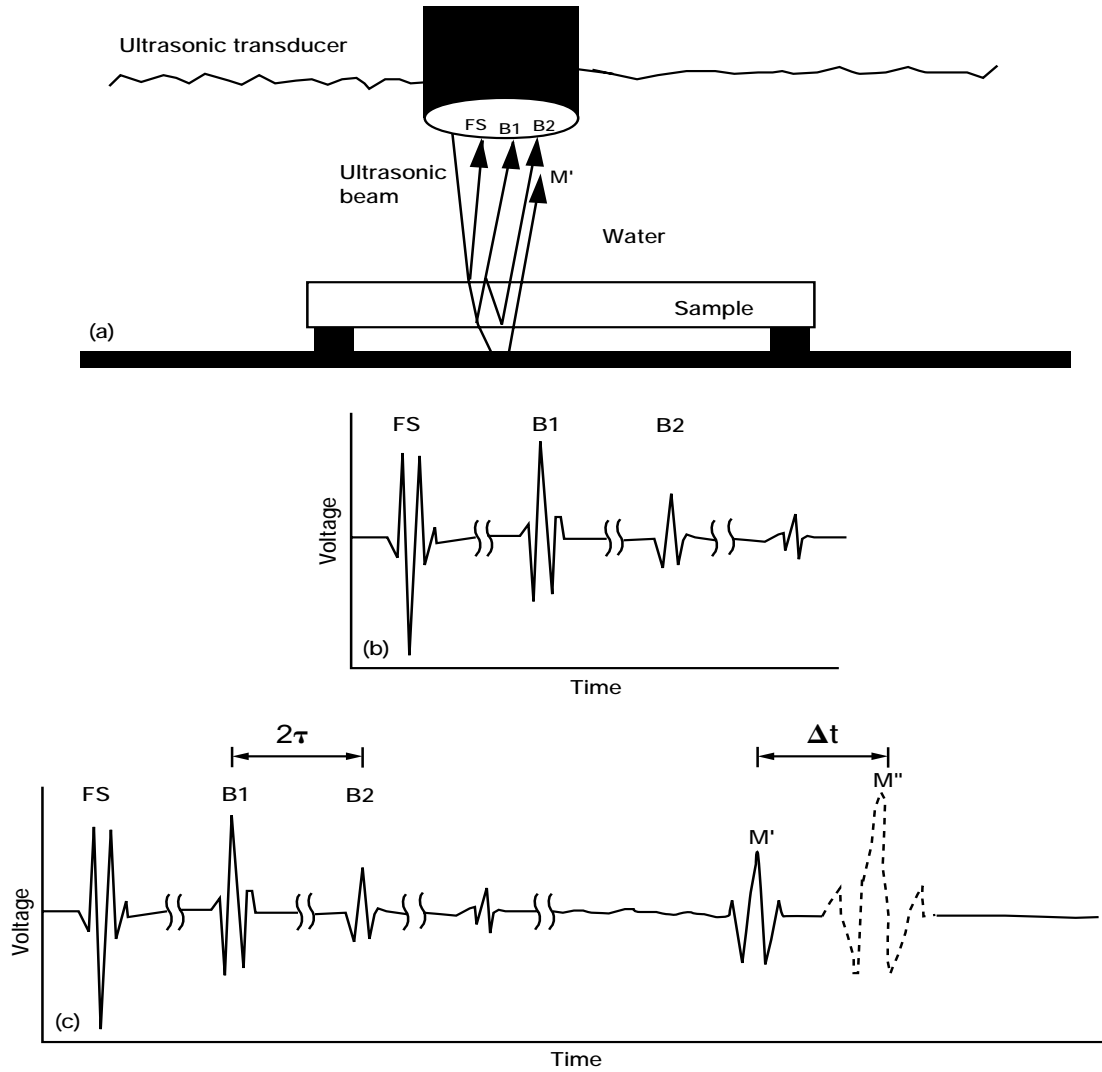
Figure 1.—Ultrasonic pulse-echo immersion testing. (a) Schematic of conventional ultrasonic pulse-echo immersion testing. (b) Waveforms of concern for thickness-based velocity imaging. (c) Waveforms s of concern for thickness-independent reflector plate velocity imaging.

$$V = c\left(\frac{\Delta t}{2\tau} + 1\right) \tag{2}$$

where c is the velocity of ultrasound in the fluid, 2τ is again the time difference between 2 successive back surface echoes and Δt is the time difference between the first echo off the reflector plate with and without the sample present, respectively. This method is heretofore described as thickness-independent reflector plate (TIRP) velocity method.

The advantage of the TIRP method over the thickness-based method is that it does not require priori knowledge of sample thickness and if extended to multiple measurements across the sample (imaging), sample thickness variation effects are eliminated. This can reduce quality control costs as the requirement for precision machining to achieve uniformly thick samples is negated. Thus, a resulting ultrasonic image using the TIRP method is not affected by thickness variation within the sample and true microstructural variation is presented. The disadvantage of the method is that it requires multiple scans and significant pulse amplitude to obtain a useable echo off the reflector plate with the sample present in the path of the ultrasonic beam. Additionally, it is critical that the fluid temperature remains nearly constant (within ±0.3 °C) throughout the scans to obtain accurate images. The latter issue is not a serious one in a large water tank (≥0.3785 m³ [100 gallons]) such as those used in conventional ultrasonic systems located in rooms with reasonable environmental control. However, for smaller tanks such as those used in tabletop scan systems, a constant temperature bath system is recommended.

Velocity imaging requires performing ultrasonic scans over an ordered array of points across the surface of a sample and for accurate calculation, digitization of entire echoes or wave trains containing multiple echoes is required. In the Sonix implementation, RF b-scans are run to digitize and store wave trains (ref. 11). Calculation of the velocity images is subsequently performed using Feature Scan option (ref. 11) for the thickness-based velocity method or Velocity/Thickness option for the TIRP method. Flow charts and detailed procedures to accomplish velocity imaging with the Sonix system are given in the Appendix.

SONIX COMMERCIAL IMPLEMENTATION

This section shows results of the implementation of thickness-based and TIRP velocity imaging in the Sonix ultrasonic immersion c-scan system. Changes in images as a result of changing scan parameters are emphasized. This allows the potential user to become acquainted with the Sonix interface and at the same time determine what scan setups may be appropriate for their velocity imaging application. Images are sometimes shown directly as Sonix system screen captures.

Materials: The materials used in this study to illustrate the implementation results were monolithic silicon nitride ceramic disks and wedges containing areas of higher-than-average (HTA) pore fraction and density gradients, and a 12-ply unidirectional polymer matrix composite (PMC) panel containing thickness and fiber volume fraction variations. The ceramic disk was 3.500 ± 0.005 mm thick and 40 mm in diameter and contained 6 distinct areas of HTA pore fraction located 60° apart and also contained a smooth pore fraction gradient from edge to center (fig. 2). The ceramic wedge was initially similar in thickness to the disk before being machined to provide a 300 μm edge-to-edge thickness gradient (lengthwise). The fiber volume fraction variations in the PMC were ~10%.

Basic Configuration: Experiments used the Sonix 8100 analog-to-digital (A/D) converter board having 100 MHz bandwidth and 8-bit resolution. Higher effective sampling rates were obtained using the Sonix Equivalent Time Sampling (ETS) algorithm (ref. 11) and velocity images were obtained using an 800 MHz sampling rate unless otherwise noted. For the ceramic materials unless otherwise noted, a 20 MHz unfocused longitudinal wave transducer with 3 mm element diameter was used for the scans and positioned ~30 mm above the samples. For the polymer matrix composite (PMC) sample, a 3.5 MHz longitudinal wave focused transducer with 12 mm element diameter was used for the scans and positioned ~30 mm above the sample. Velocity was calculated using a cross-correlation computer algorithm (ref. 12) contained in the Sonix software to obtain time delay, and images are shown with 248 discrete levels of gray scale that appear continuous to the eye. A 486DX2/33 MHz was the processor.

C-scan vs. Velocity Images: Figure 3 shows c-scan images of the ceramic disk obtained with the Sonix system. 360 by 360 scan points with scan increment of 0.11 mm were used for the scan. Figures 3(a) and (b) were obtained by scaling to 248 gray levels the amplitude and time of occurrence (time-of-flight [TOF]), respectively, of the peak

100 μm

1 cm

Lighter
region

Lighter
region

Center

Right
ridge

Left
edge

Average porosity through section thickness, percent
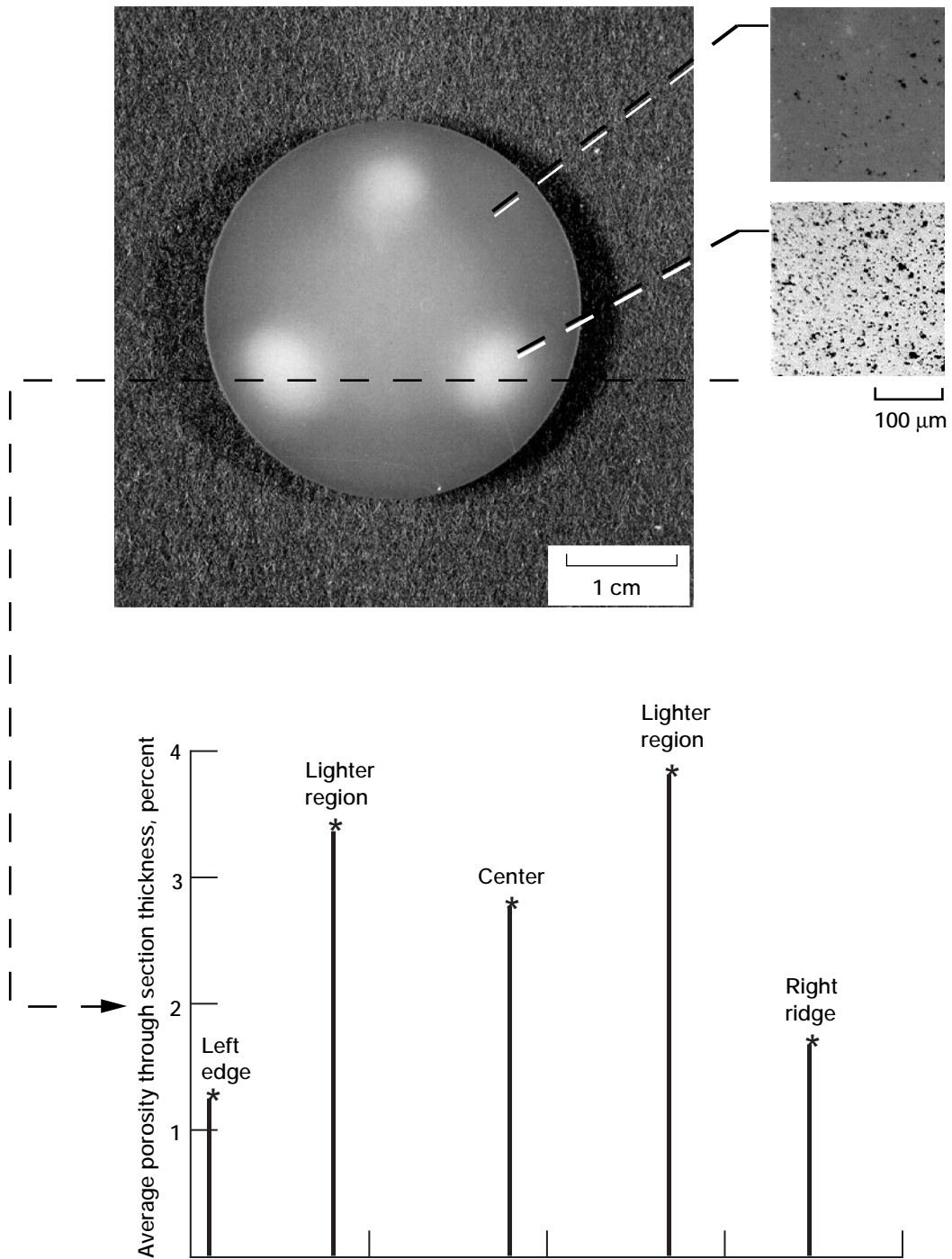
4

3

2

1

Figure 2.—Optical photograph of ceramic disk with higher-than-average pore fraction areas.
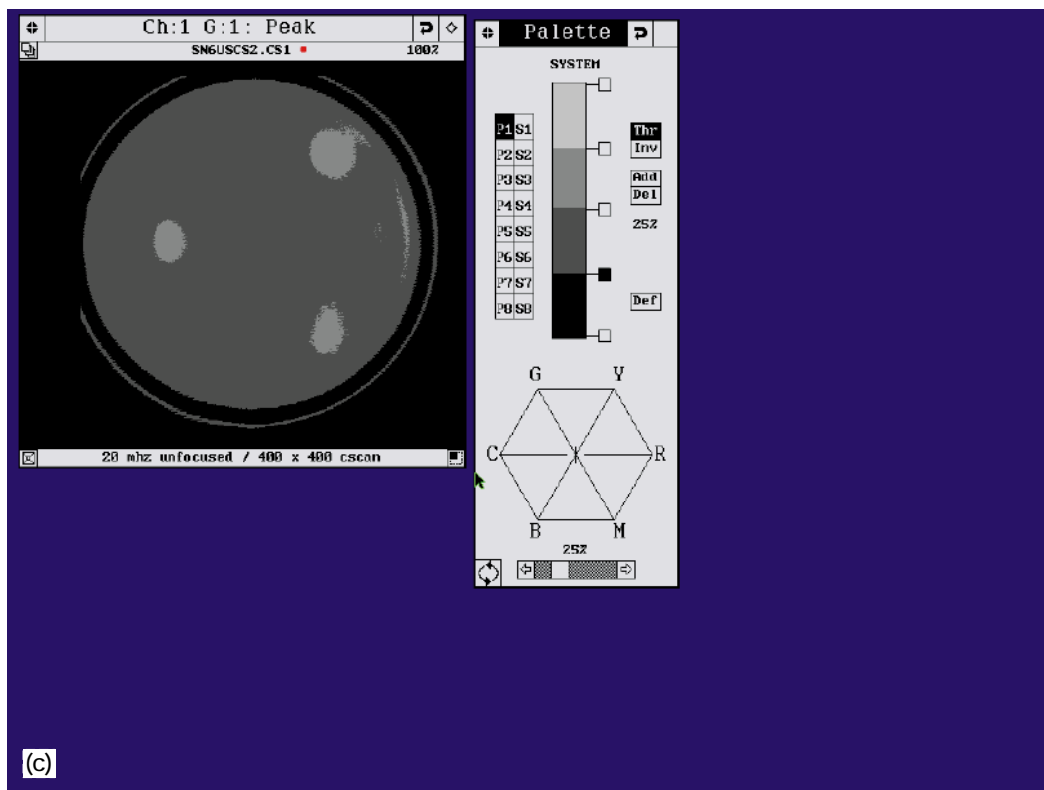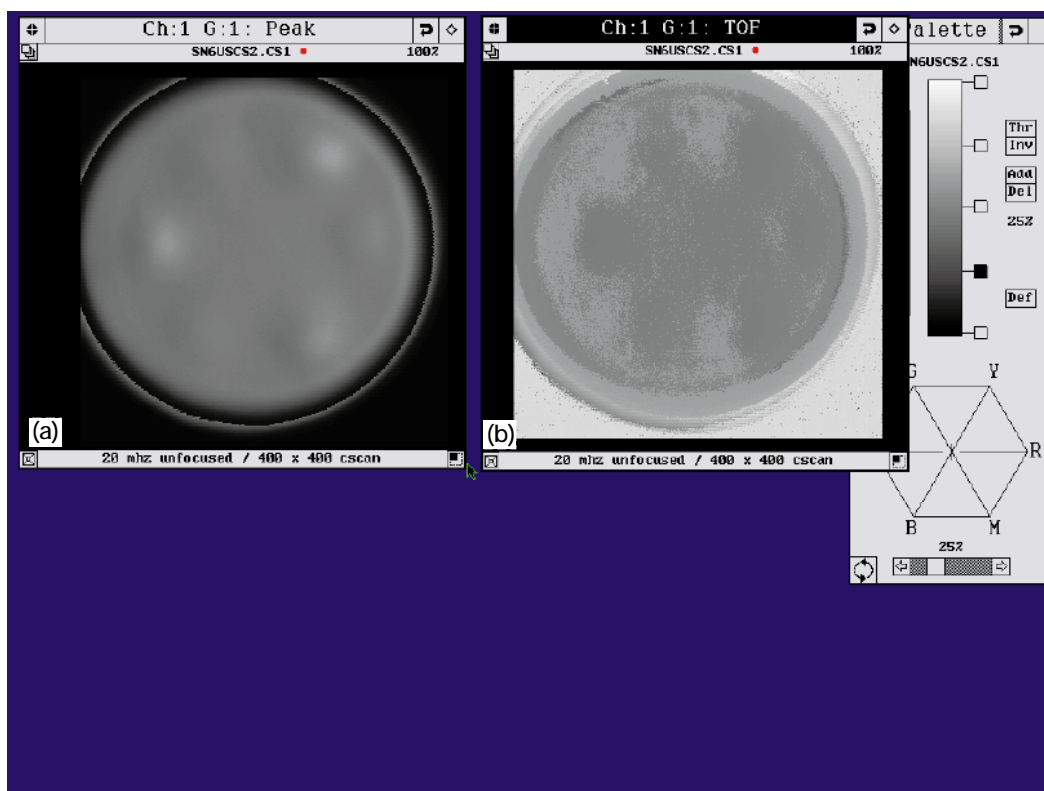
Figure 3.—C-scan images of ceramic disk obtained with the Sonix system gating first back surface echo b1. (a) Peak amplitude image. (b) Time-of-flight image. (c) Peak amplitude image using thresholding method to highlight higher-than-average pore fraction regions.

of the first back surface echo. (The Front surface follower gate (ref. 11) was ON so that back surface echo TOF variations due to nonlevelness of the disk setup were eliminated. Combining the latter with the fact that the disk was of nearly uniform thickness, the variations seen in the TOF image were solely due to microstructural variation.) The c-scan was completed in ~5 mins. Viewing of both images reveals some variation in the sample (aside from the banding apparent at the edges that is due to diffraction). Figure 3(c) shows the peak amplitude c-scan (fig. 3(a)) after using a thresholding technique whereby the gray scale consists of 4 shades rather than 248. Three of the HTA pore fraction regions become clearly visible using this method but the other 3 are masked. None of the c-scan images show the edge-to-center pore fraction gradient. Using a 20 MHz focused transducer produced similar images although the banding effect was not as pronounced.

Figure 4 shows the thickness-based velocity image of the same disk obtained with the same experimental setup as for the scans of figure 3. Note how clearly the six areas of high-than-average pore fraction variations and the edge-to-center density gradient are revealed as compared to the c-scan images of figure 3. Velocity variation was shown to be around 10.6 to 11.1 mm/μsec with high pore fraction areas (dark spots) near 10.6 mm/μsec and edge areas (light-colored) near 11.1 mm/μsec. This image is a demonstration of the resolution capabilities for velocity imaging. Normally, it is recommended that the scan increment for velocity imaging be no less than 0.5 mm since fine increment velocity imaging requires relatively significant scan and processing time (due to digitization and storage of entire wave trains). This image required 3 hr of scan and processing time.

Effect of Scan Increment and Smoothing on Image Quality: Figure 5 shows thickness-based velocity images of the ceramic disk illustrating improved resolution of microstructure in the ceramic disk as the scan increment is decreased from 5 to 2 to 1 to 0.1 mm. Unfocused 20 MHz transducer was used. Figure 5(c) shows the velocity image obtained with the 1 mm scan increment for a 40 by 40 point scan. The scan and processing time to obtain this image was ~3 min. Note that the image of figure 5(c) is somewhat pixilated due to the coarse 1 mm scan increment but reveals similar features to the image generated with a 0.1 mm scan increment. Figure 5(e) shows the image of figure 5(c) after applying smoothing from the c-scan "Process" menu to eliminate the pixilation. This velocity image is nearly identical to that seen for a similarly-smoothed cross-correlation velocity image obtained using an ultrasonic contact scan procedure with 1 mm scan increment (fig. 5(f)) (ref. 5).

Thickness-based vs. Thickness-independent Reflector Plate Velocity Images: Figure 6(a) shows a thickness-based velocity image of the ceramic wedge. 40 by 80 scan points with a scan increment of 0.5 mm were used for the scan. The wedge was uniformly thick to 0.002 mm and contained 3 areas of HTA pore fraction and a density gradient from edge-to-center which are revealed in the velocity image. Figure 6(b) shows the velocity image of the same wedge obtained using identical scan parameters but with the TIRP methodology. Note the quantitative and qualitative similarity between the 2 images which is expected due to the near-perfect thickness uniformity.

Figure 7(a) shows a thickness-based velocity image of the same wedge after machining a smooth 300 μm thickness gradient from edge-to-edge lengthwise (thickness greater at top). The image shows about a 10 percent velocity variation from the top-to-bottom edge due to the thickness and microstructural variations. Note that the HTA pore fraction area at the top of the disk is accentuated while the lower HTA pore fraction area is masked totally by the thick-ness gradient. Figure 7(b) shows a TIRP velocity image of the machined wedge. Note that the lower HTA pore fraction area is revealed and the top HTA area is de-emphasized giving the correct qualitative and quantitative representation of microstructural variation in the wedge. Note also how similar the images of figure 6(a), (b), and 7(b) are which is expected if the methodologies are performed properly.

Figure 8(a) shows a back surface echo peak amplitude c-scan image of a PMC sample. A 100 MHz sampling rate and a 0.25 mm scan increment were used for the c-scan. The c-scan shows variable gray scale indications throughout the panel, including a 50 by 50 mm central region where 2 dark (low amplitude) spots are seen (fig. 8(b)). These darker regions were found to have on average 10 percent lower volume fraction fiber than that of surrounding regions after metallographic preparation followed by optical image analysis. Note that a 60 μm thickness variation was measured for this central region. Figure 8(c) shows a thickness-based velocity image of the central region obtained using an 800 MHz sampling rate and a 1 mm scan increment. The velocity image shows similar features to that of the c-scan. Figure 8(d) shows a TIRP velocity image of the central region. Similar features are seen to that of the images of figures 8(b) and (c). However, the TIRP velocity image quantifies most accurately the true microstructural variation in the region which is ~10 percent in terms of velocity variation. Also, the increased contrast between light and dark areas in the TIRP velocity image (fig. 8(d)) as compared to that in the thickness-based velocity image (fig. 8(c)) indicate that the thickness variation in the central region partially masked the microstructural (fiber volume fraction) variation. The difference in the histogram of velocity values after elimination of thickness variation effects is shown in figures 8(e) and (f).
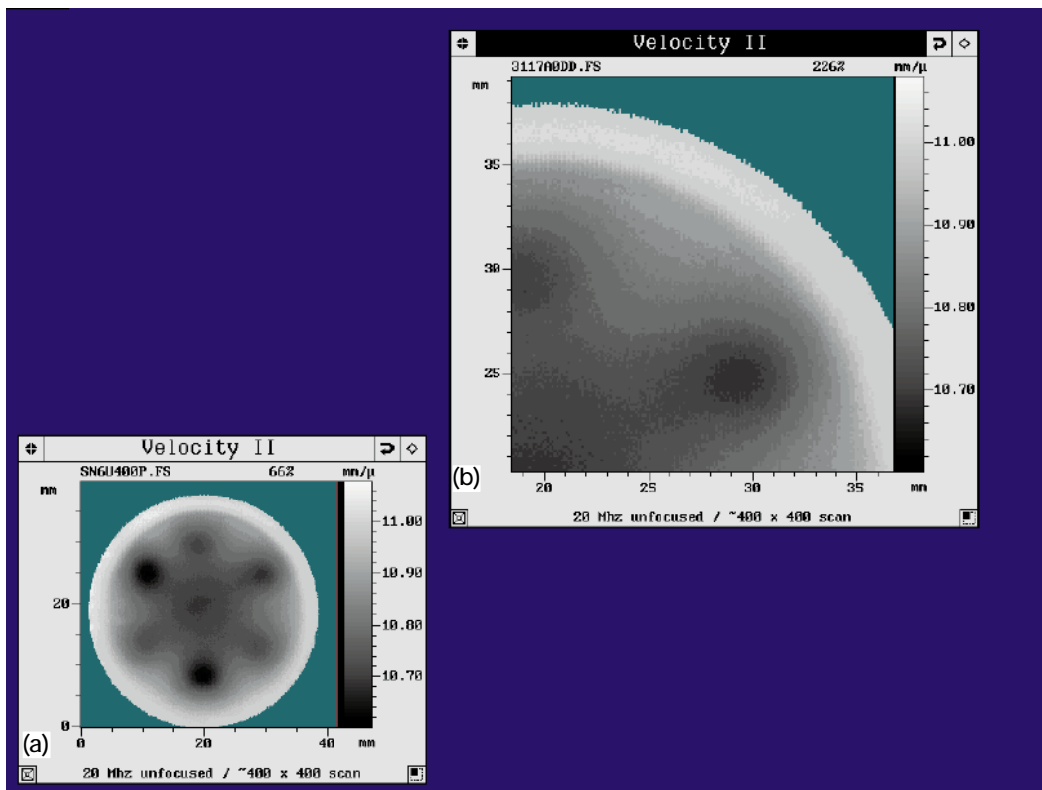
Figure 4.—Thickness-based velocity image of ceramic disk. (a) Image of full disk. (b) Magnified image of northeast quadrant of disk.
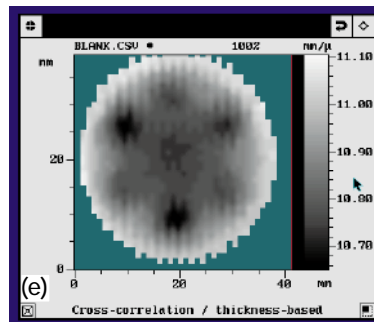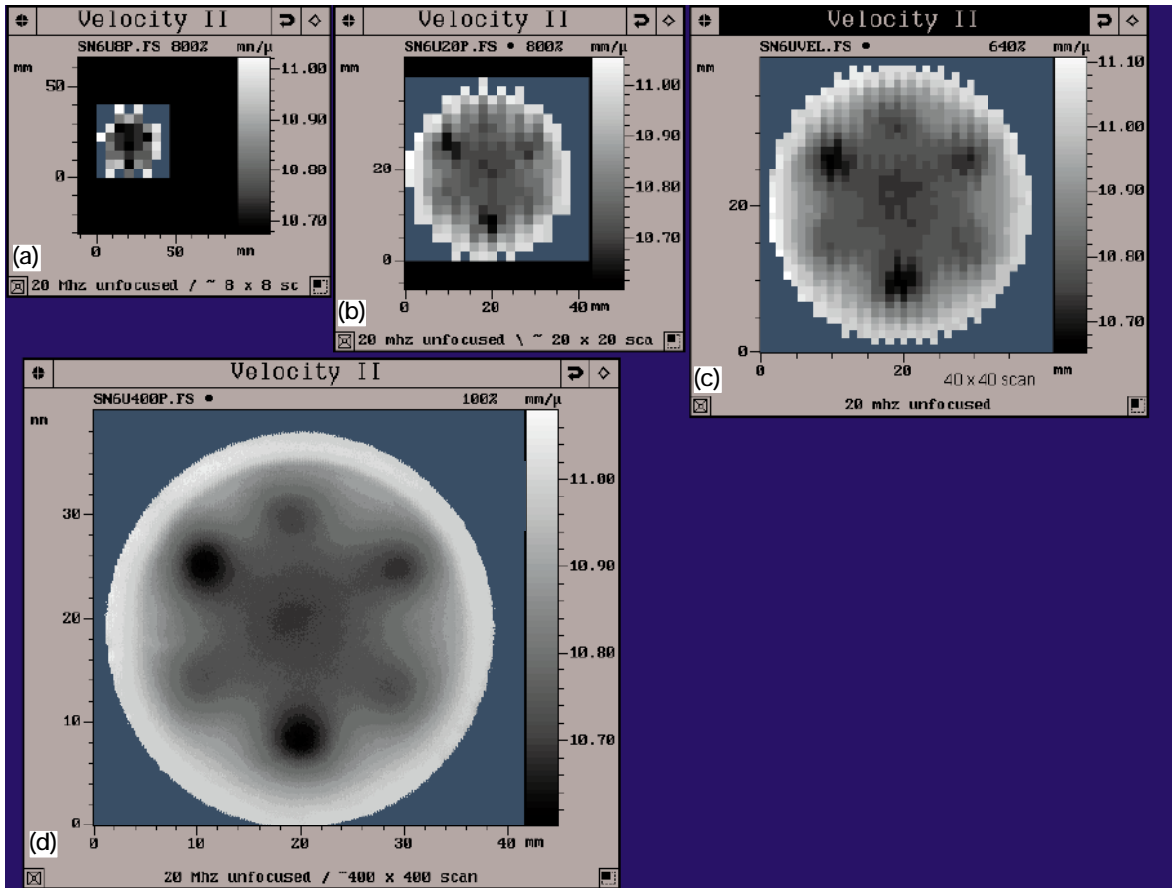
Figure 5.—Effect of scan increment and smoothing on quality of velocity images of ceramic disk. (a) 5 mm. (b) 2 mm. (c) 1 mm. (d) 0.1 mm. (e) Image of (c) after smoothing. (f) Velocity image of similar ceramic disk obtained with contact scan system with 1 mm scan increment, 50 MHz transducer, 9-bit A/D converter, 1 GHz A/D sampling rate, followed by smoothing image.

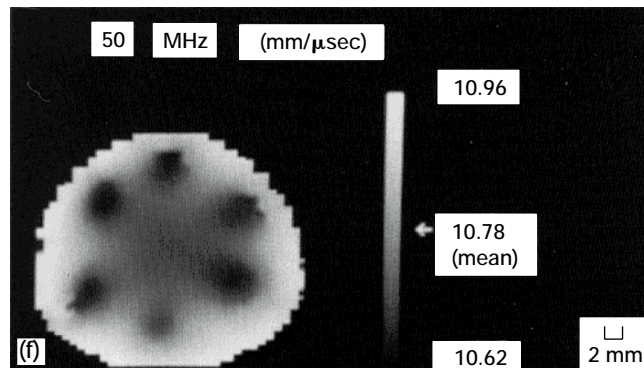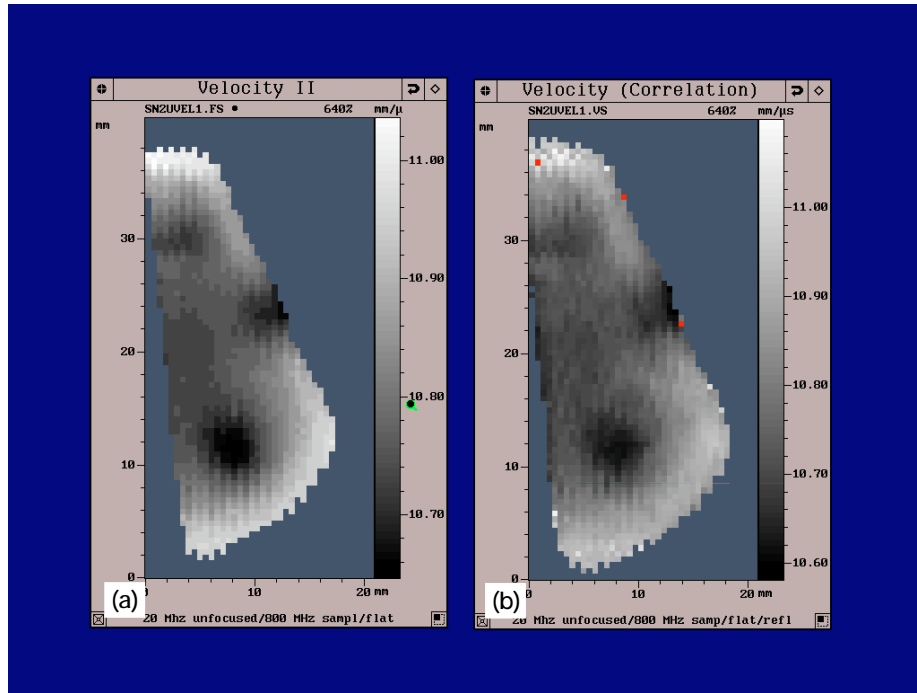Figure 6.—Thickness-based vs. thickness-independent reflector plate velocity images of uniformly-thick ceramic wedge. (a) Thickness-based velocity image. (b) Thickness-independent velocity image.
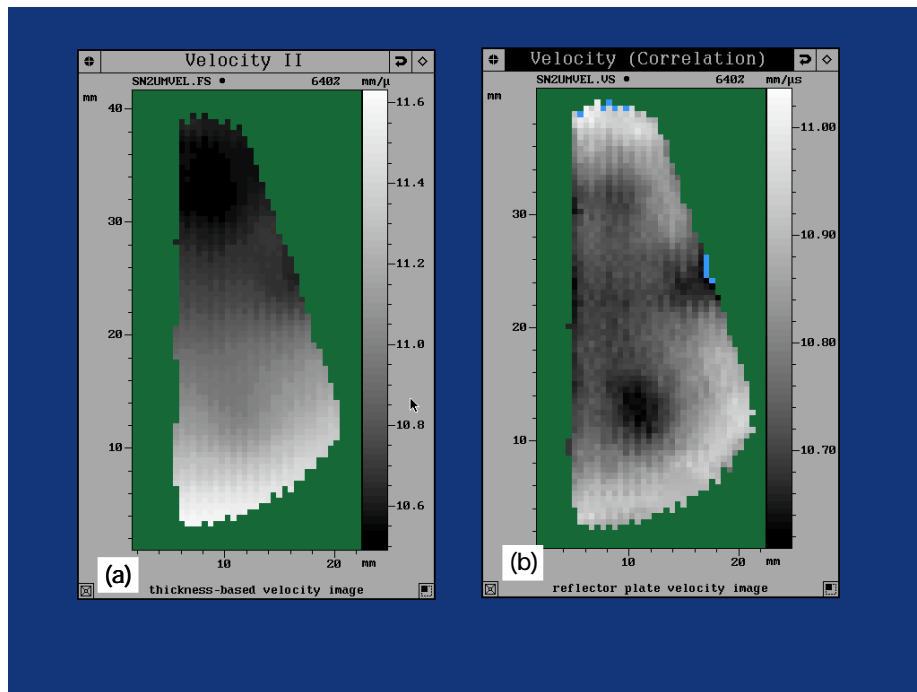
Figure 7.—Thickness-based vs. thickness-independent reflector plate velocity images of ceramic wedge after machining 300 μm edge-to-edge thickness gradient (length-wise). (a) Thickness-based velocity image. (b) Thickness-independent velocity image.
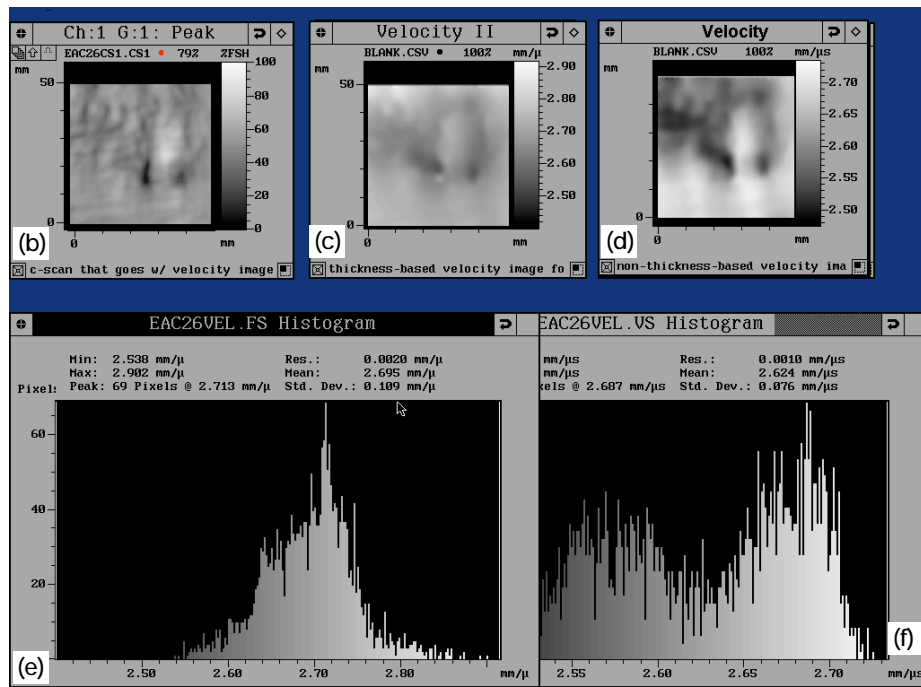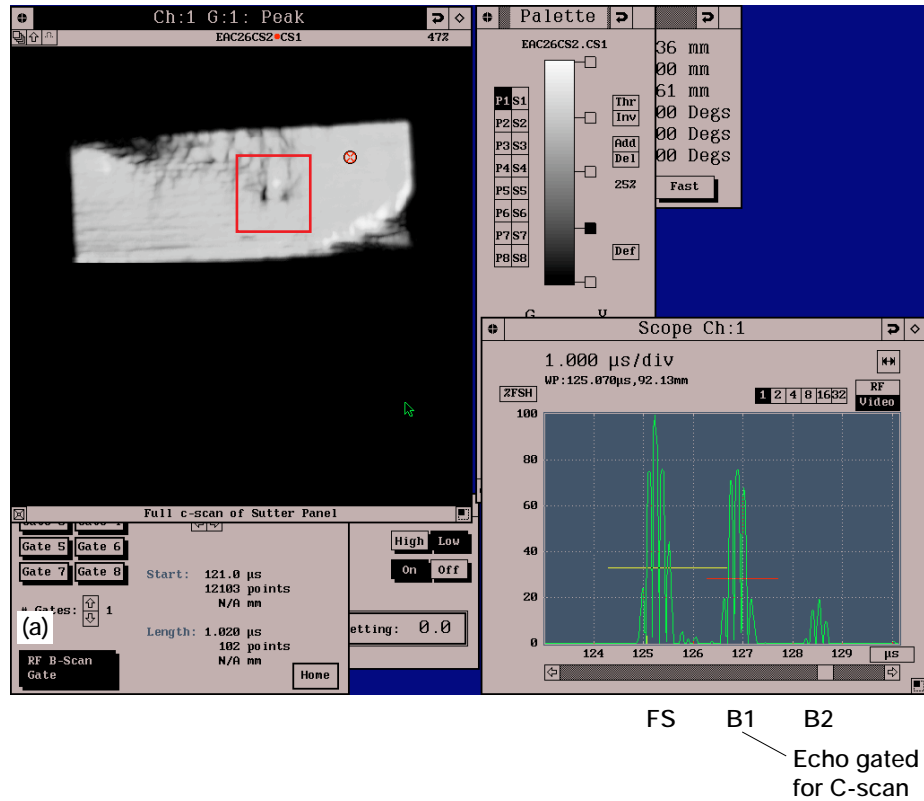
Figure 8.—Ultrasonic images of polymer matrix composite sample. (a) C-scan of sample. (b) C-scan of middle region of sample showing nonuniform gray scale pattern. (c) Thickness-based velocity image of region in (b). (d) Thickness-independent velocity image of region in (b). (e) Histogram of velocity values for thickness-based velocity image. (f) Histogram of velocity values for thickness-independent velocity image.

Flagging Out-of-Bounds Scan Points and Extreme Value Filtering: Based on the LeRC-developed Post Scan Interactive Data Display (PSIDD) computer program (ref. 13) for contact scans, Sonix developed methods to allow flagging of scan points where velocity values are not within predetermined bounds. This type of analysis allows one to reform the velocity image using extreme value filtering of bad points to view finer microstructural detail if necessary. Figure 9(a) shows a TIRP velocity image of the ceramic disk before performing extreme value filtering. Note that the HTA pore fraction areas and edge-to-center density gradient are not clearly resolved because the few extreme value velocity points increase the total velocity range significantly. The extreme velocity values resulted from very low signal-to-noise ratio waveforms at edge areas of the sample making the velocity calculations suspect. Viewing the image of figure 9(a) and its histogram of velocity values in figure 9(b), most velocity values are seen to fall in the range of ~10.6 to 11.1 mm/μsec. Performing out-of-bounds points flagging with bounds set at 10.37 and 11.171 mm/μsec produces the image in figure 9(c) with values outside of the specified range flagged with red (values ≥11.171 mm/μsec) and blue (values ≤10.37 mm/μsec) colors to contrast with the gray scale image. Figure 9(d) shows the image of figure 9(c) after extreme value filtering: the flagged points are replaced with an average of 4 to 8 nearest neighbors. Note that the HTA pore fraction areas and edge-to-center density gradient are clearly resolved in figure 9(d).

Reviewing Velocity Values and Raw Wave trains Associated with Individual Scan Points: Based on the LeRC-developed Post Scan Interactive Data Display (PSIDD) computer program (ref. 13) for contact scans, Sonix developed methods to allow reviewing the velocity value and raw wave train data acquired at any scan point. This feature has proven extremely useful in pinpointing and evaluating sample locations where microstructural quality is suspect or when improper digitizations have occurred, and for comparative analysis at different scan points within a sample. Figure 10 shows the velocity value and the 4 waveforms (B1, B2, and 2 reflector echoes) associated with a scan point of coordinates x=8, y=27 on the image of the ceramic disk formed using the TIRP method. Note that a valid velocity value was obtained at this scan location with a very low amplitude echo off the reflector plate with the sample present. Another feature available is showing line plots of velocity values at a horizontal or vertical line in the image. Figure 11 shows line plots comparing for the thickness-based and TIRP method the results of one horizontal line of velocity values.

Effect of Analog-to-Digital Sampling Rate on Image Quality: Figure 12 shows thickness-based velocity images of the ceramic disk illustrating the improved resolution of microstructure in the ceramic disk as A/D sampling rate is increased from 100 to 800 MHz. Use of A/D sampling rates ≥800 MHz resulted in no appreciable increase in image resolution. 40 by 40 scan points with a scan increment of 1 mm were used for the scans.

Effect of Unfocused vs. Focused Transducer on Image Quality: The thickness-based velocity images of the ceramic disk obtained using focused and unfocused 20 MHz transducers were very similar as shown in figure 13. An 800 MHz sampling rate and a scan increment of 1 mm were used for these 40 by 40 mm scans.

Cross-correlation vs. Peak-to-Peak Time Difference Calculation Method: Figure 14 shows thickness-based velocity images illustrating the use of cross-correlation algorithm vs. positive peak-to-peak to calculate time delay for the velocity image. Note (1) the more accurate resolution of defects in the image using cross-correlation and (2) the absolute velocity values are 20 percent more accurate using cross-correlation using values obtained from a contact scan procedure as reference (fig. 5(f)). This result is likely due to the fact that cross-correlation uses the entire pulse to calculate time delay rather than just the peaks which tend to oscillate on the waveform at different scan points. 800 MHz sampling rate and 1 mm scan increment was used in these 40 by 40 mm scans.

Additional Features: The Feature Scan velocity imaging module also contains an option to perform thickness (d) mapping by inputting a constant material velocity value (V) for the material under test and calculating time delay between echoes B1 and B2 according to:

$$d = \frac{2\tau V}{2} \tag{3}$$

In the method of eq. (3), microstructural variation effects that influence echo time-of-flight will decrease the accuracy of thickness determination. The Velocity/Thickness Imaging module has an option to perfom *true* thickness mapping that is independent of microstructural effects. Thickness is determined from (ref. 10):

$$d = \frac{(\Delta t + 2\tau)c}{2} \tag{4}$$
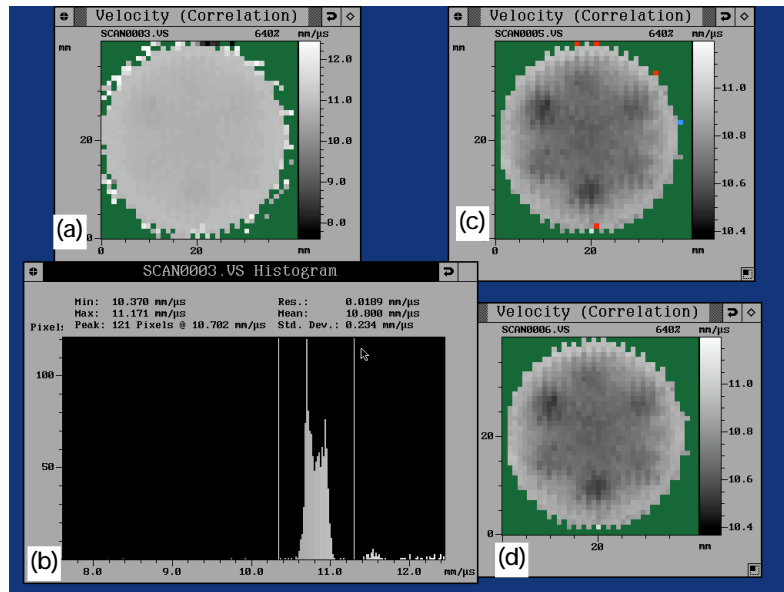
Figure 9.—Thickness-independent reflector plate velocity images of ceramic disk. (a) Before extreme value filtering. (b) Histogram of velocity values of image in (a). (c) Flagging values outside specified bounds. (d) After replacing flagged points with average of nearest neighbors.
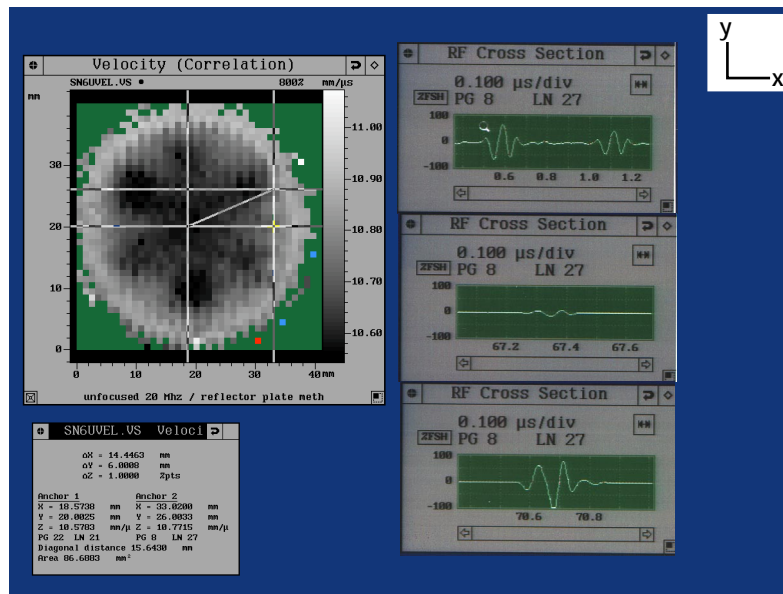
Figure 10.—Using cursor on image to recall velocity values and raw waveforms. x = Position (mm), y = position (mm), z = velocity (mm/μsec), PG = increment in y-direction, LN = increment in x-direction.
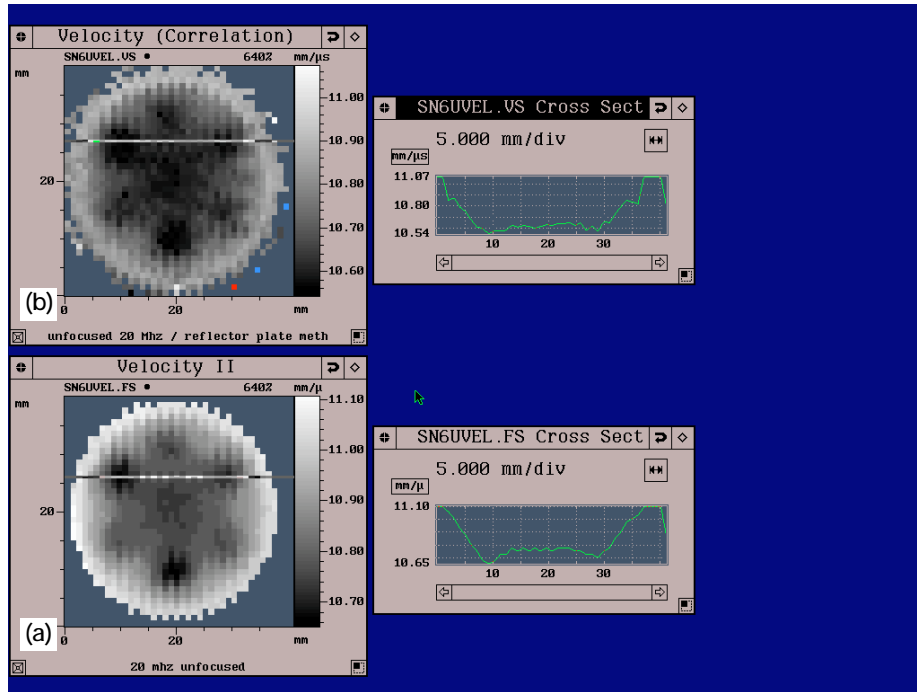
Figure 11.—Plot of velocity vs. position for 1 scan line. (a) Thickness-based velocity image. (b) Thickness-independent velocity image.
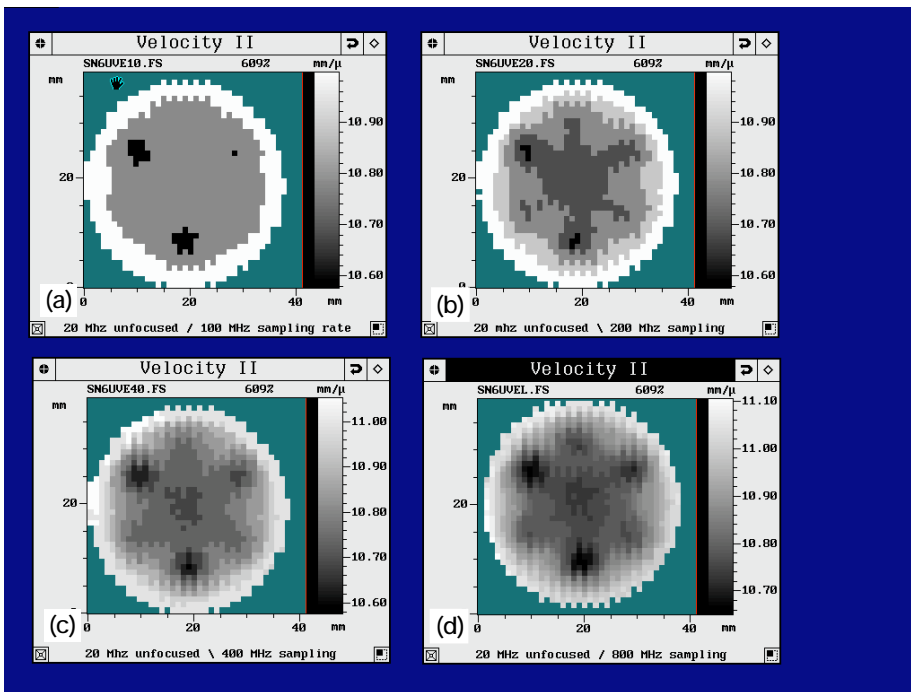
Figure 12.—Effect of analog-to-digital sampling rate on quality of velocity image of ceramic disk. (a) 100 MHz. (b) 200 MHz. (c) 400 MHz. (d) 800 MHz.
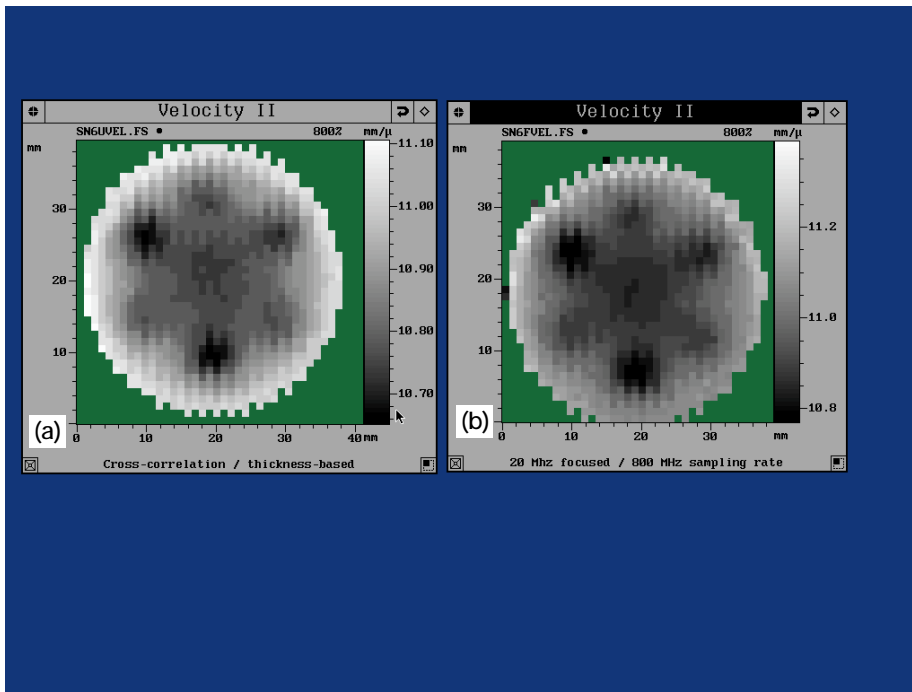
Figure 13.—Effect of unfocused vs. focused transducer on quality of velocity image of ceramic disk. (a) Unfocused. (b) Focused.
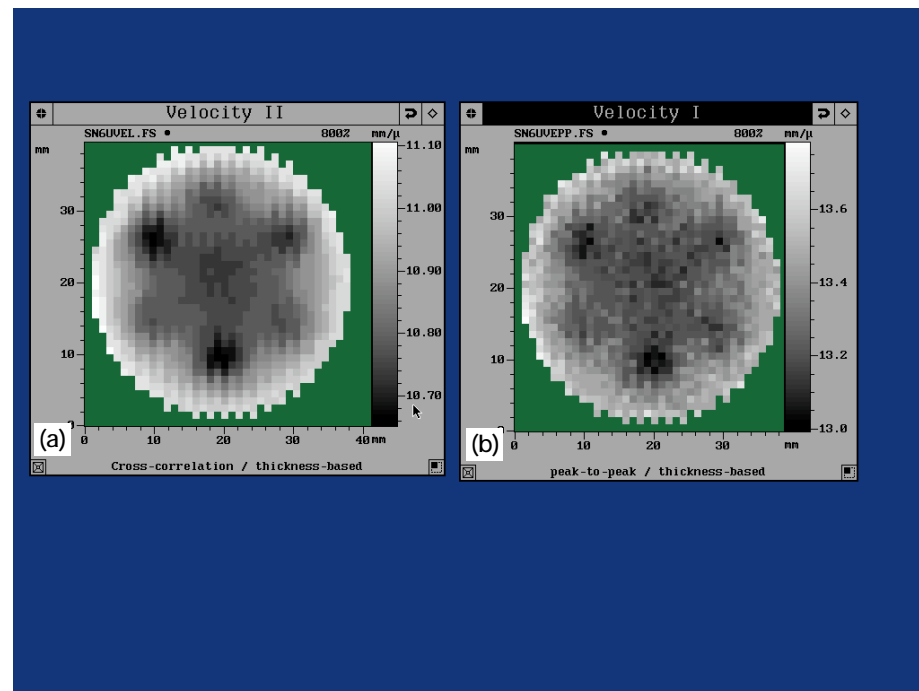
Figure 14.—Effect of calculation method on quality of velocity image of ceramic disk. (a) Cross-correlation method. (b) Peak-to-peak method.
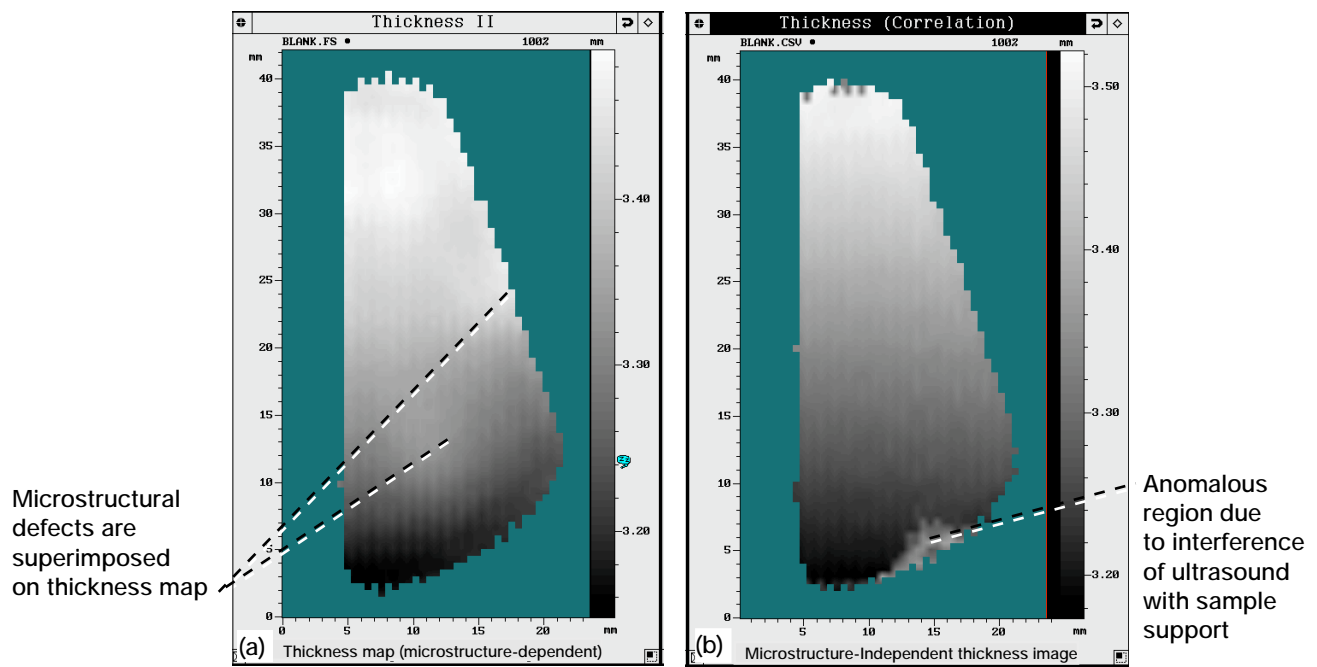
Figure 15.—Thickness maps of ceramic wedge. (a) Using eq. (3): microstructure-dependent method. (b) Using eq. (4): microstructure-independent method.

These options would be of interest to those concerned with precision thickness mapping of components such as plates and hollow tubes. Figure 15 shows thickness maps of the ceramic wedge having the 300 μm thickness gradient as obtained using eqs. (3) and (4). 40 by 80 scan points with a scan increment of 0.5 mm were used for the scan. The thickness map of fig. 15(b) agrees almost identically (within 1%) with thickness measurements made by micrometer.

SUMMARY & SIGNIFICANCE

The Lewis-developed velocity imaging methods being implemented by Sonix significantly enhance the materials characterization capabilities of ultrasonic imaging. Velocity imaging allows the quantitative characterization of microstructural variations and associated physical property variations. Among the benefits of the Lewis-transferred methods is that of elimination of sample thickness variation effects. This isolates ultrasonic variations due to material microstructure; cost savings can therefore be realized because the ultrasonic image can be correctly interpreted without the need for additional machining for thickness control during nondestructive evaluation stages of material development. These attributes constitute a major improvement over the capabilities of conventional ultrasonic methods.

We see the cooperative effort between NASA-Lewis and Sonix as an effective means for transferring our technology for worldwide availability while helping to improve the product of a domestic firm. The aerospace and other materials development-intensive industries which use extensive ultrasonic inspection for process control and failure analysis will now have an alternative, highly accurate imaging method available in commercial form.

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10. Roth, D.J.: Single Transducer Ultrasonic Imaging Method That Eliminates the Effect of Plate Thickness Variation in the Image. NASA TM-107184, 1996.
11. Ultrasonic C-scan Users Guide, V3.10d, January, 1995. Sonix, Inc. 8700 Morrissette Drive, Springfield, VA 22152.
12. Hull, D.R.; Kautz, H.E.; and Vary, A.: Measurement of Ultrasonic Velocity Using Phase-Slope and Cross-Correlation Methods. Mater. Eval., vol. 43, no. 11, 1985, pp. 1455-1460.
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APPENDIX: SONIX CROSS-CORRELATION VELOCITY IMAGING FLOW CHARTS AND OPERAT-
ING PROCEDURES

I. Thickness-based Velocity Imaging

Flow Chart:

Obtain Sample Thickness.

↓

Place sample in tank and position transducer so that first front surface echo (FS) and 2 successive back surface echoes (B1, B2) are visible in digital oscilloscope.

↓

Fill in c-scan setup window for desired scan area and scan increment and set A/D ETS Sampling Rate to 800 MHz if using Sonix 8100 A/D. If using Sonix 81G 1 GHz A/D, do not use ETS sampling.

↓

Set front surface follower gate and 2 data gates on FS, B1, and B2, respectively. Data gates are threshold sensitive. Set RF B-scan gate to cover the union of data gates 1 and 2. Echoes also should not be allowed to clip during scan.

↓

Perform Full B-scan. It is recommended that step size equals scan increment established in c-scan setup. Save parameter and RF B-scan files.

↓

Click on the B-scan image window to examine phase relationships of B1 compared to B2 at several scan locations.

↓

Select "Feature Scan" under Process menu.

↓

Set up B1,B2 data gates in RF cross-section window as done during RF b-scan.

↓

Select "Features" from F-scan gate control. Select "Velocity II" from Features menu and fill in required information in pop-up menu and then click on "OK." Click on "F-scan GO" in F-scan gate control window to form image. Save parameter and image files.

↓

Perform Image Post-processing as needed.

Operating Procedures:

A. Scan Setup and Data Collection. (Note that the procedures outlined here discuss using 2 successive back sur-face echoes [B1 and B2]; it is possible to use the first front surface (FS) and first back surface (B1) echoes as the two needed echoes if the material and experimental conditions do not allow a second back surface echo (B2) of suf-ficient amplitude. If it is needed to use FS and B1, substitute FS for B1 and B1 for B2 in the procedures below.)
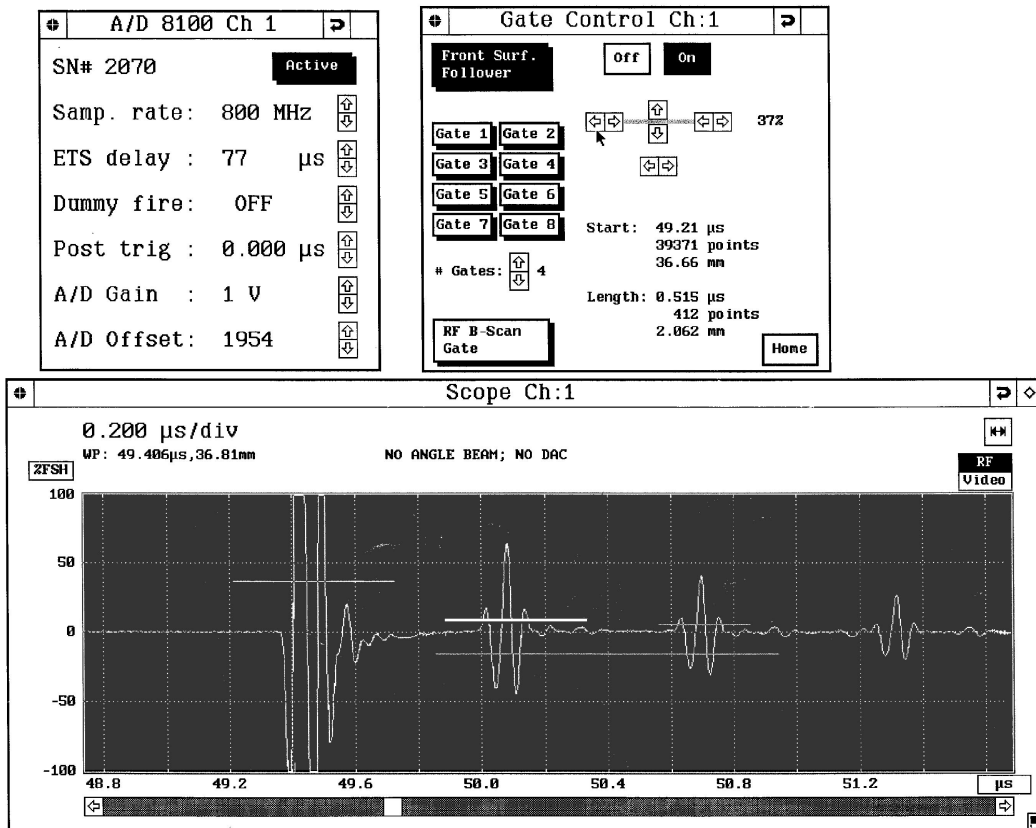
(1) Measure sample thickness (mm) at several locations, obtain an average value and range, and then place the sample in the immersion tank. Position the transducer over the center of the sample so the first front surface echo and 2 successive back-surface echoes are seen in the digital oscilloscope display. Put oscilloscope in RF mode (fig. A1). Establish scan start (choice under scan menu). The transducer should be positioned above the sample at distances dete-rmined initially by the focal distance. At this point, adjust the transducer Z-position for maximum BACK surface echo amplitude. (If an unfocused transducer is being used, ref. A1 has a list of recommended ranges of transducer-to-sample distances based on transducer element size and frequency. A good initial starting height is approximately 1to 2" for most unfocused transducers.)

(2) Under scan menu, click on c-scan setup, and set the c-scan setup appropriately for the desired scan area and resolution (fig. A2). It is recommended that the scans be run with an increment of ≥0.5 mm so that the size of the scan (remember, the echoes are being digitized and stored) and the time of the scan are reasonable. Depending on setup, user may want to change scan axis to be the y-axis. Under Windows menu, click on A/D board, and SET A/D ETS SAMPLING RATE TO 800 MHz if using the Sonix 8100 A/D board. More desirable would be to have the Sonix 81G 1 GHz A/D board when fully operational for velocity imaging so that ETS sampling is not needed. Lower sampling rates than 800 MHz will provide representative but coarse images. It is recommended to scan at scanner velocity and acceleration settings that minimize waveform jitter due to manipulator bridge vibration.

(3) Turn the Front Surface Follower Gate (FSFG) ON and set it on the front surface echo of the sample appro-priately as done for c-scans (remember the threshold sensitive nature of the FSFG). Focus attention on the 2 succes-sive back surface echoes (B1 and B2). Try to make B1 and B2 echo amplitudes about 30 to 80 percent of the oscilloscope display height by adjusting pulser-receiver attenuation/gain and/or Sonix A/D gain. Turn data gates 1 and 2 on, and hit "home" to have gates show up on scope. Set data gates 1 and 2 individually over the successive back surface echoes with data gate 1 on B1. DATA GATES 1 AND 2 ARE THRESHOLD SENSITIVE WHICH MEANS THAT THE HEIGHT OF THE DATA GATE MUST BE SET SO THAT THE ECHO PEAK EXCEEDS THE GATE HEIGHT FOR THE SCAN OVER THE SAMPLE (but not for the scan over outlying areas surrounding sample as for example outlying areas surrounding a circular disk within a square area scan). The threshold sensitive feature is included to distinguish background from valid sample data. This can be accomplished by initially "manu-ally" running the transducer over the scan area while viewing the echo heights. IT IS IMPORTANT NOT TO HAVE ECHOES CLIP DURING SCAN. The gates must also cover the extent of the echoes (don't be chintzy here!). Turn on the RF B-scan gate and set it to cover the union of data gates 1 and 2. The RF B-scan data gate is NOT threshold sensitive. Hit "Follows = Yes" for B-scan gate.

(4) Perform Full B-scan (choice under Scan Menu). In order to have the rf b-scan step size equal to the scan in-crement specified in c-scan setup, set rf b-scan "steps (frames)" equal to the "step data points + 1" specified during your c-scan setup (procedure A2) (fig. A3). (For your information, only the RF gate will move during the B-scan while the data gates will remain stationary although they maintain their respective positions with regard to the RF gate.) After the scan, return to scan start. Do not change setup (gate positions, lengths, and thresholds) before saving the parameter and image files. Save parameter and image files (choices under File Menu).

(5) Click on the B-scan image window to examine phase relationships of B1 compared to B2 at several scan loca-tions. This examination will allow you to note whether the echoes are the same polarity or phase-inverted with re-spect to each other (fig. A4). Page down using arrow key to ~ halfway thru B-scan image window where 2 good band patterns are visible. Under Visualize menu, select "cross-section," and place the cursor on the RF B-scan im-age so that the B1, B2 wave train is shown in the RF cross-section window (fig. A5). This allows the user to view the stored waveforms. Resize RF cross-section window both laterally and vertically as desired so that a better pic-ture of the echoes is seen. Move cursor up and down in the RF B-scan image to see various B1,B2 echo patterns. If desired, page through the RF B-scan image windows and repeat the latter process. Because the phase relationship between the echoes is likely to be the same at scan locations throughout the sample unless significantly different material properties are encountered, it is felt that examination of the phase relationships at several locations is valid to make a decision for the whole sample. These phase relationships are important for the computation of the velocity image and are usually very obvious. Note whether the echoes are phase-inverted or of same polarity with respect to each other.

A/D 8100 Ch 1

SN# 2070   [Active]

Samp. rate: 800 MHz

ETS delay :   77   µs

Dummy fire: OFF

Post trig :   0.000 µs

A/D Gain :   1 V

A/D Offset: 1954

Gate Control Ch:1

Front Surf. Follower   [Off] [On]

[Gate 1] [Gate 2]
[Gate 3] [Gate 4]
[Gate 5] [Gate 6]
[Gate 7] [Gate 8]

372

Gates: 4

[RF B-Scan Gate]

Start: 49.21 µs
     39371 points
     36.66 mm

Length: 0.515 µs
     412 points
     2.062 mm   [Home]

Scope Ch:1

0.200 µs/div
WP: 49.406µs,36.81mm   NO ANGLE BEAM; NO DAC

[2FSH]   [RF] [Video]

100
50
0
-50
-100

48.8   49.2   49.6   50.0   50.4   50.8   51.2   µs

A-1

SCAN SETUP

[Linear]   [Cylindrical]   [Polar]

Scan Axis Length: 40.6400   mm

Step Axis Length: 20.3200   mm

Scan Data Points: 80   [Aspect]

Step Data Points: 40

Scan Time (est.): 0:46   [Max Speed]

Total disk space: 0.0   MegaBytes

Scan Increment: 0.50800 mm

Step Increment: 0.50800 mm   Scan Axis: Y-Axis

Scan Acceleration: 151.12 mm/sec²   Step Axis: X-Axis

Scan Velocity: 60.959 mm/sec

Compound Step: [On] [Off]   Bidirectional: [On] [Off]

Line-in-Space: [On] [Off]   Current Scan Pos.:   [Center] [Corner]

[Show Scan]   [Go]   [OK]   [Cancel]

A-2

B-Scan Setup

Steps (Frames): ⬆⬇ _41

File Size: 0.8 Megabytes

Step Size: 0.5 mm

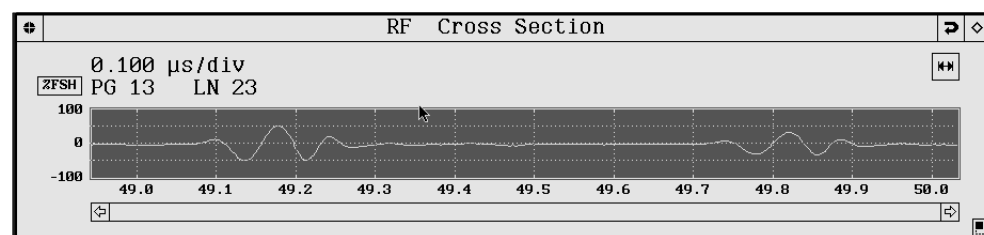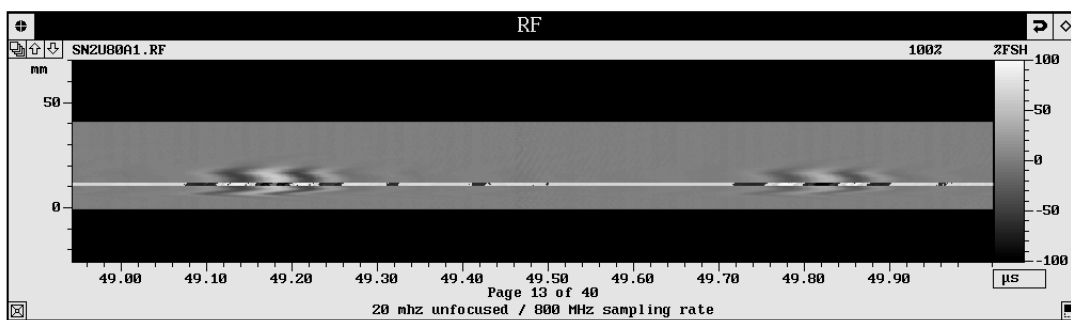| Go | Cancel |

A-3

(a)   B1   B2

(b)   B1   B2
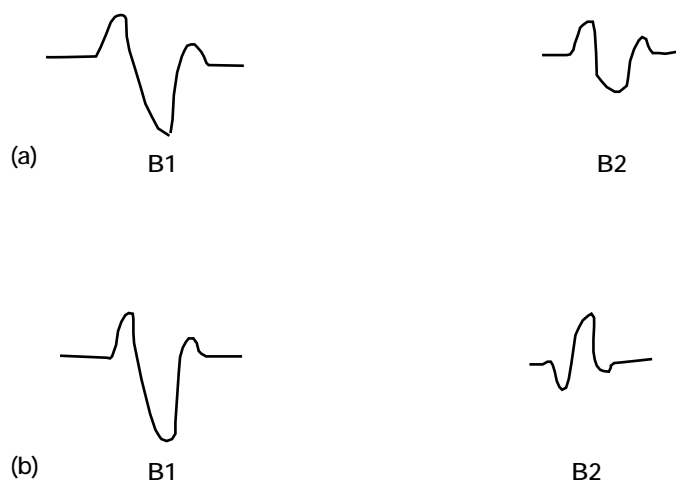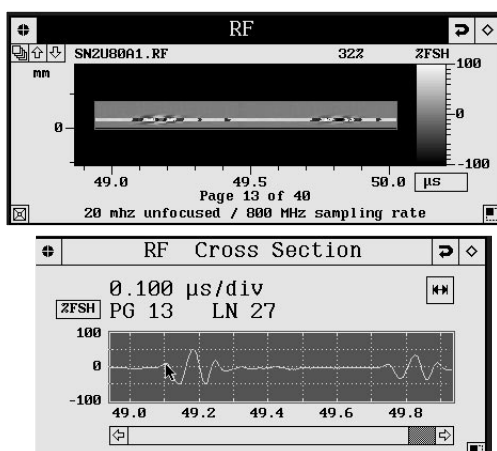
A 4.— (a) B1 and B2 are same polarity (b) B1 and
B2 are phase-inverted.

A-5

A-6

B. Velocity Image Formation

(1)   Under File menu, load RF B-scan image and parameter file obtained in Thickness-based velocity imaging data acquisition procedure (procedure A4). Open the oscilloscope and c-scan gate control windows (opening the oscilloscope window allows the gate information in the c-scan gate control window to update correctly.)

(2) Click on the B-scan image window. Page down using arrow key to ~ halfway thru scan where 2 good band patterns are visible. Under Process menu, select "Feature Scan." The RF cross-section and F-scan gate control windows will pop-up. Under Visualize menu, select "cross-section," and place the cursor on the RF B-scan image so that the B1, B2 wave train is shown in the RF cross-section window. This allows the user to view the stored waveforms. Resize RF cross-section window both laterally and vertically as desired so that a better picture of the echoes is seen (fig. A6). Move cursor up and down in the RF B-scan image to see various B1,B2 echo patterns. If desired, page through the RF B-scan image windows and repeat the latter process.
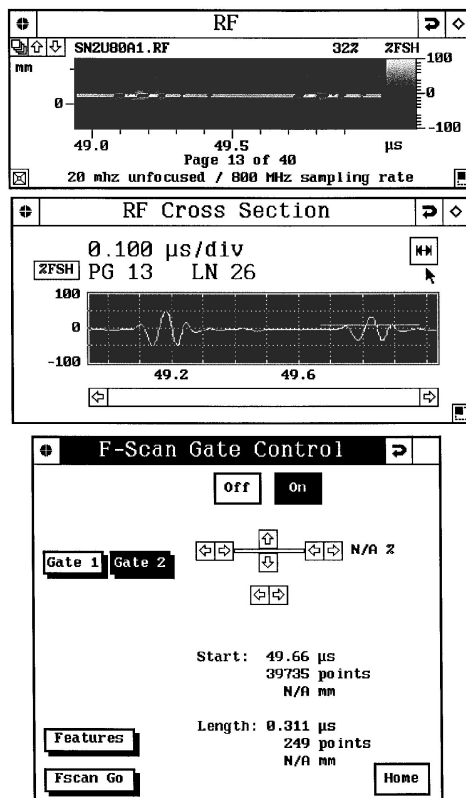
(3) Select gate 1 in the C-scan and F-scan gate control windows. Focus attention on RF cross-section window. Using the gate information in the C-scan gate control window as a guide, set up F-scan gate 1 over echo B1 similar to the way it was setup during the Thickness-based velocity imaging data acquisition procedure (procedure A3) (fig. A7). Select gate 2 in the F-scan gate control window and set up F-scan gate 2 over echo B2 similar to the way it was setup during the Thickness-based velocity imaging data acquisition procedure (procedure A3). As in the latter procedure, FEATURE SCAN GATES ARE THRESHOLD SENSITIVE. Save a new parameter file, writing over previous parameter file (saved in procedure A4) if you so choose.

(4) Select "Features" from F-scan gate control. Select "Velocity II" from Features menu (fig. A8). A window for user input will pop up (fig. A9), and the user should enter sample thickness (mm) and the thickness variation/ measurement error (mm) (the latter is determined from the difference of the max and min thicknesses obtained while measuring sample thickness plus any systematic error in the thickness measuring device), and select Image Range = Full and background = color. Specify ABS, Same Polarity, or Phase Inv for B1,B2 echoes phase relationship. (No bounds can be entered for an image where the Full Range is displayed.) Click on "OK" in pop-up window and click on "F-scan GO" in F-scan gate control window to form the velocity image. A "% complete" status line will be displayed so that the user can track progress of image formation. IF IMAGE SHOWS DATA VALUES OUTSIDE THE BOUNDS OF THE SAMPLE (for example in the region outside of a circular disk specimen), IT IS LIKELY THAT F-SCAN GATES WERE SET TOO LOW AND NOISE VALUES WERE PROCESSED FOR VELOCITY. RAISE THE F-SCAN GATES SLIGHTLY AND PERFORM FEATURE SCAN AGAIN (repeat steps B3 and B4).
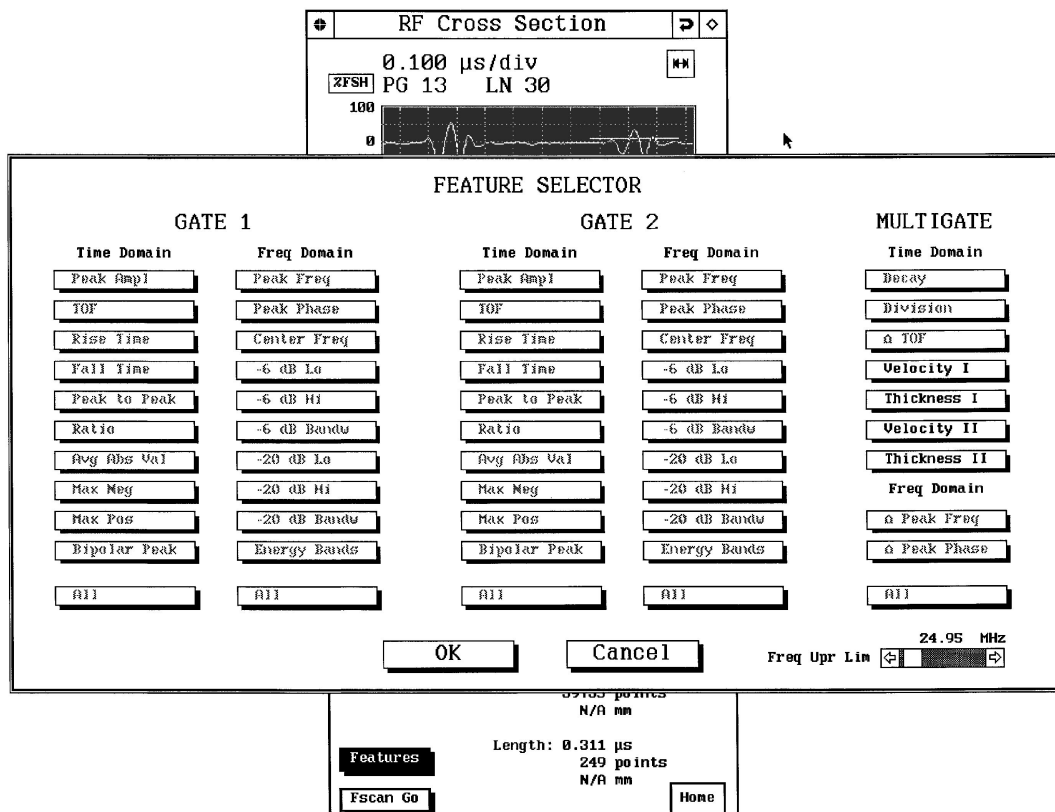

C. Velocity Image Post-processing

(1) After image formation is complete, analyze the image using "Show Histogram" under Process menu. Histogram display shows bars in gray scale values corresponding to gray values in image (fig. A10). If it is desired to see the histogram bars in white, open the palette window and select S8 default color scheme. Adjust the lower hinge on the color bar to 100 percent using the slide bar at the bottom of the box. The histogram is useful for examining the range of output values. If the histogram contains stray values that are significantly outside the main distribution of values, it is likely that setting new, tighter bounds that filter out stray values and performing a revised image formation (performing step B4) with these bounds will significantly increase the resolution of inhomogeneity.

(2) The following step should be used only to flag/filter extreme high and/or low values. After examining the histogram, if it is desired to flag extreme high and/or low values, use the mouse to drag the palette hinge points at each end of the histogram display to the desired locations such that new bounds are defined. Record the minimum and maxi-mum seen at the top of the histogram display, or move the histogram display to an unimpeded position so that these values will show up after "Features" is reselected from the F-scan gate control. Repeat procedure B4 with the following modifications: Image range = bounded and enter the minimum and maximum bounds just discussed. The user can also use: Image range = Exp +/- Tol option which represents "Expected value plus or minus a tolerance." For the latter, the user is to enter an expected value for the constant and a tolerance value. For either option, if it is desired to FILTER out-of-bounds (flagged) values, set Filter = on. When Filter = on, flagged pixels are replaced by the gray scale average of its 8 nearest unflagged neighbors if in the interior of the image or its 3 or 5 nearest unflagged neighbors if on the border of the image. With Filter = off, flagged pixels will be demarcated red (above upper bound) and blue (above lower bound). The user can also select Image Range = Gate Xtnts which will flag/filter values based on (1) the minimum time-of-flight (TOF) used to calculate velocity set to gate 2 starting time

RF

SN2U00A1.RF 32% ZFSH

mm

100

0

0

-100

49.0   49.5   µs

Page 13 of 40

20 mhz unfocused / 800 MHz sampling rate

RF Cross Section

0.100 µs/div

ZFSH PG 13   LN 26

100

0

-100

49.2   49.6

F-Scan Gate Control

Off On

Gate 1 Gate 2

N/A %

Start: 49.66 µs
        39735 points
        N/A mm

Length: 0.311 µs
        249 points
        N/A mm

Features

Fscan Go   Home

A-7

RF Cross Section

0.100 µs/div

ZFSH PG 13   LN 30

100

0

FEATURE SELECTOR

GATE 1		GATE 2		MULTIGATE
Time Domain	Freq Domain	Time Domain	Freq Domain	Time Domain
Peak Ampl	Peak Freq	Peak Ampl	Peak Freq	Decay
TOF	Peak Phase	TOF	Peak Phase	Division
Rise Time	Center Freq	Rise Time	Center Freq	∆ TOF
Fall Time	-6 dB Lo	Fall Time	-6 dB Lo	Velocity I
Peak to Peak	-6 dB Hi	Peak to Peak	-6 dB Hi	Thickness I
Ratio	-6 dB Bandw	Ratio	-6 dB Bandw	Velocity II
Avg Abs Val	-20 dB Lo	Avg Abs Val	-20 dB Lo	Thickness II
Max Neg	-20 dB Hi	Max Neg	-20 dB Hi	Freq Domain
Max Pos	-20 dB Bandw	Max Pos	-20 dB Bandw	∆ Peak Freq
Bipolar Peak	Energy Bands	Bipolar Peak	Energy Bands	∆ Peak Phase
All	All	All	All	All

24.95 MHz

OK   Cancel   Freq Upr Lim

39735 points
N/A mm

Length: 0.311 µs
        249 points
        N/A mm

Features

Fscan Go   Home

A-8

RF Cross Section

0.100 µs/div
ZFSH PG 13   LN 30
100
0

VELOCITY II (Cross Correlation)

Thickness: mm

Echo Correlation: Abs
                     Same Pol
                     Phase_Inv

Image Range: Full   Exp±Tol   Bounded   Gate Xtnts
    Expected: mm/µs
    Tolerance: mm/µs
    Extreme Values: Filter

Background: Color   Black   White

Thickn Error (Optl):   mm

    OK   Cancel

G   MULTIGATE
Time Domain   Time Domain
Peak Ampl   Decay
TOF   Division
Rise Time   ∆ TOF
Fall Time   Velocity I
Peak to Peak   Thickness I
Ratio   Velocity II
Avg Abs Val   Thickness II
Max Neg   Freq Domain
Max Pos   ∆ Peak Freq
Bipolar Peak   ∆ Peak Phase

All   All

                                           24.95 MHz

89183 points
N/A mm
Length: 0.311 µs
        249 points
        N/A mm

Features

Fscan Go   Home

A-9

Velocity II
SN2UVEL1.FS   640Z   mm/µ

flat sample / thickness-based velocity

SN2UVEL1.FS Histogram

Min: 10.626 mm/µ   Res.:   0.0016 mm/µ
Max: 11.036 mm/µ   Mean: 10.809 mm/µ
Pixel: Peak: 250 Pixels @ 10.731 mm/µ   Std. Dev.: 0.121 mm/µ

A-10

minus gate 1 ending time and (2) the maximum time-of-flight (TOF) used to calculate velocity set to gate 2 ending time - gate 1 starting time. This option is good for finding a predetermined range into which to map output values that requires no user input. From an experimenter's point of view, it is advisable NOT to turn filter ON until results of bounded analysis (with filter OFF) can be investigated.

(3) If it is desired to have a black or white background for the image, repeat procedure B4 with Background = Black or White. Note that a histogram of values is no longer valid because the background is now included in the histogram calculation.

(4) After desired image is obtained, select "Duplicate Image" under File menu. Select "Smooth" under the process menu to interpolate the image results and provide a smoother-appearing image. Save *.FS image(s). Do not overwrite image comments concerning velocity statistics.

(5) If it is desired to view individual velocity values in the full-processed or bounded velocity image, select "Locate/Measure" under the Measure menu and move white bar cursor (using mouse cursor w/left mouse cursor depressed) in image to desired scan location. Click on left mouse button to bring up Feature Window which will show x,y (mm) location and velocity value (z) in mm/μsec corresponding to that scan point where cursor is located (fig. A11). Move cursor over the image to view velocity values at all locations desired.

(6) If it is desired to view a plot of the velocity values at a particular image line, select "cross-section" under visualize menu and move white cursor bar across image by moving mouse w/left mouse button depressed (fig. A12). The cross-section bar orientation is toggled by depressing the left and middle mouse buttons simultaneously.

(7) If it is desired to view the raw waveform data corresponding to a particular scan location, select "Locate/ Measure" under the Measure menu and move white bar cursor (using mouse cursor) in originally-formed velocity (not duplicate) image to desired scan location. Click on left mouse button to bring up Feature Window which will show x,y location and velocity value (z) in mm/μsec corresponding to that scan point where cursor is located. Below this information in the Feature Window is the page (PG) and line (LN) numbers that essentially give the scan coordinates. LN corresponds to the line number in the step axis direction. PG corresponds to the scan location within an individual scan line. Click on RF image. Make sure RF image is at 100 percent magnification. Select "cross-section" under Visualize menu. This will cause RF cross-section (scope) window to pop-up (fig. A13). Move the mouse to RF image and select dhe PG desired using up/down arrows in RF image window. To select the desired LN number, move heavy white cursor (via mouse cursor w/left mouse cursor depressed) within RF image PG to the LN desired. View the RF cross-section for the raw waveform (B1, B2) data corresponding to the PG and LN numbers (scan location) selected. To repeat pro-cedure, start at beginning of this paragraph.

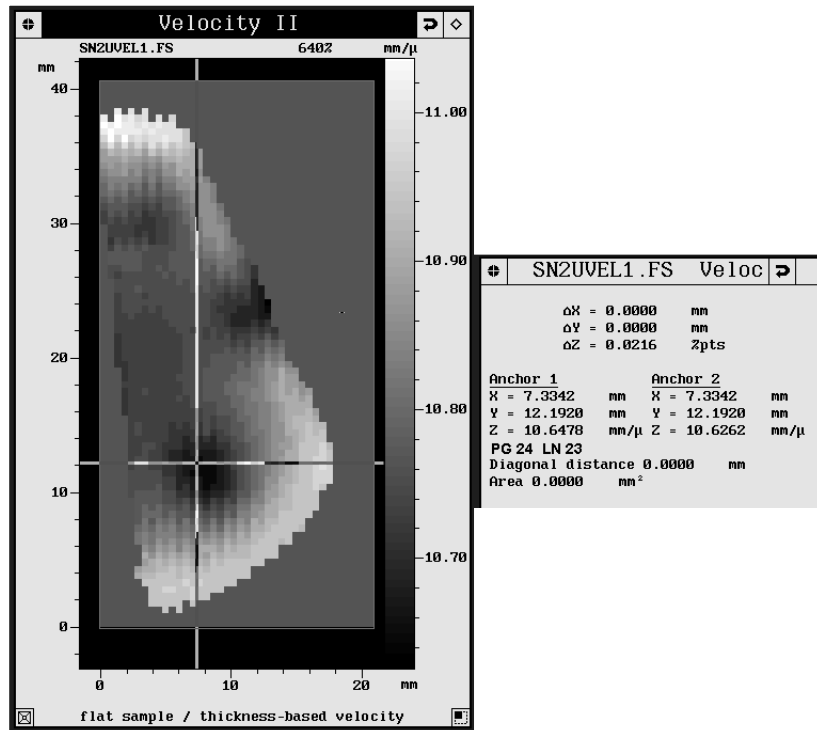## II. Thickness-independent Reflector Plate Velocity Imaging

Flow Chart:

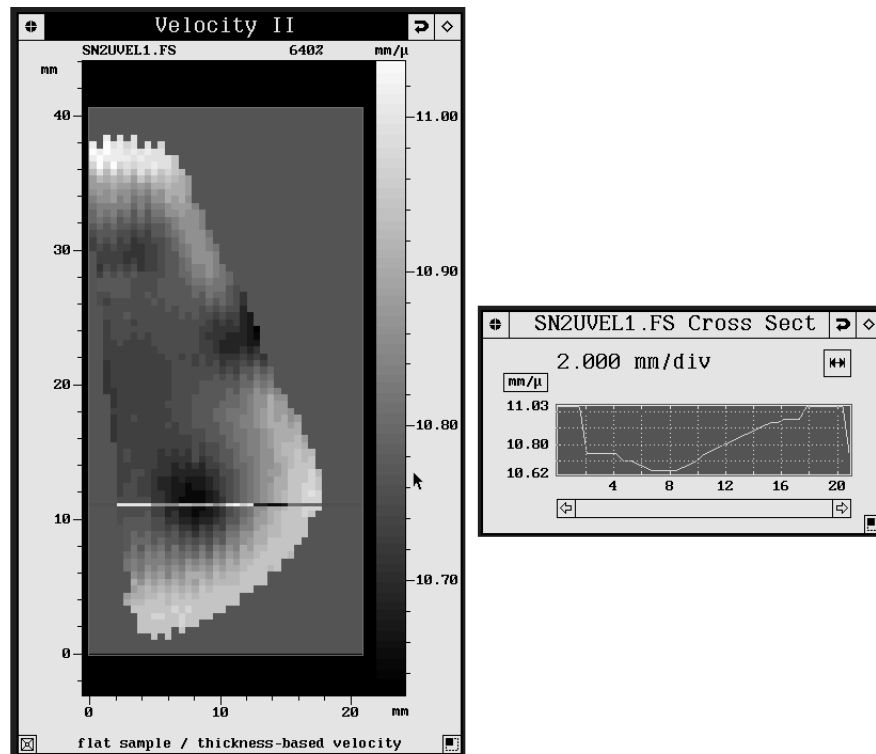| |
|---|
| Setup sample on reflector plate. Place sample in tank and position transducer so that first front surface echo (FS), 2 successive back surface echoes (B1, B2), and the first echo off reflector plate are visible in digital oscilloscope. |

Fill in C-scan setup window for desired scan area and scan increment and set A/D ETS Sampling Rate to 800 MHz if using Sonix 8100 A/D. If using Sonix 81G 1 GHz A/D, do not use ETS sampling.

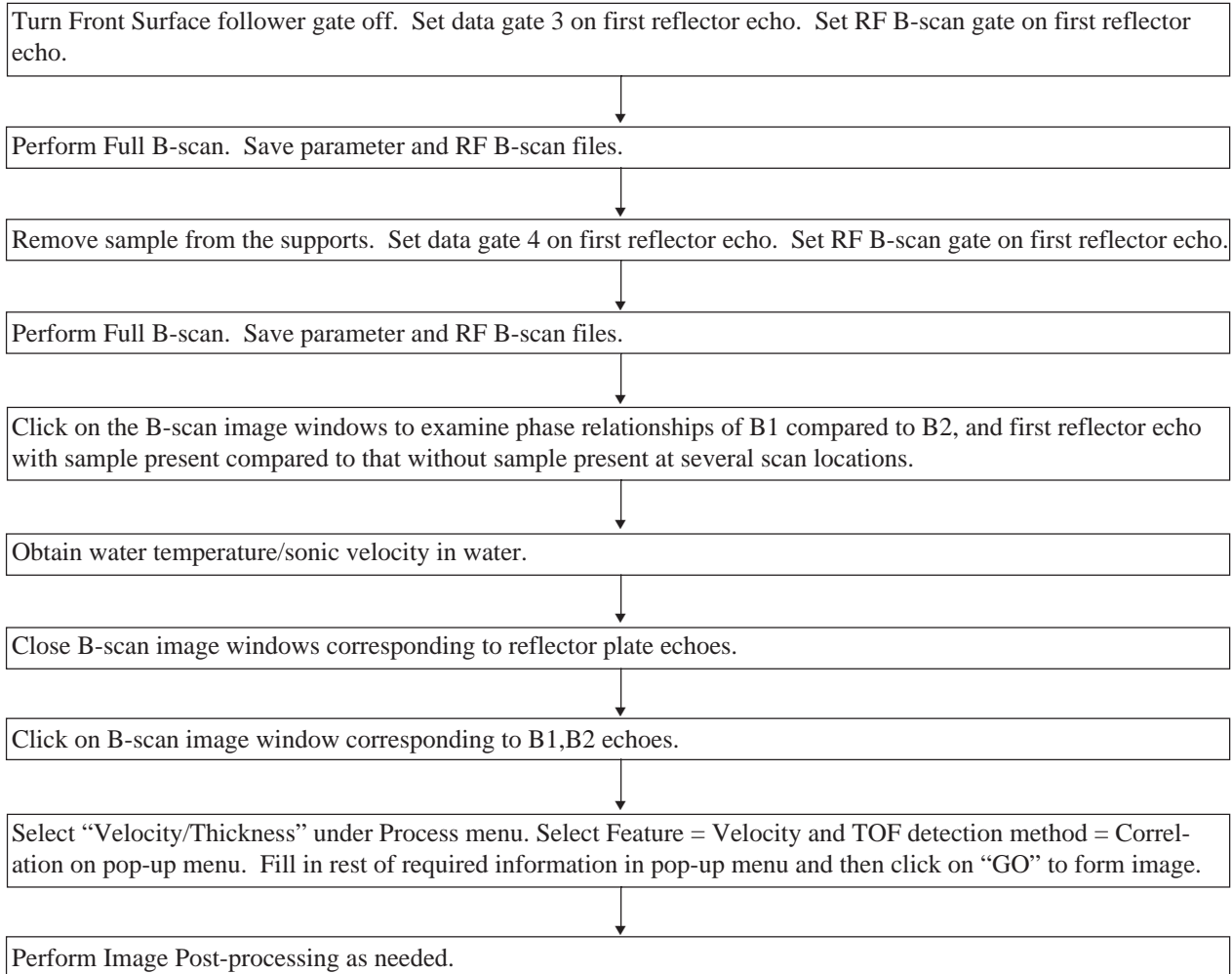| |
|---|
| Set front surface follower gate and 2 data gates on FS, B1, and B2, respectively. Data gates are threshold sensitive. Set RF B-scan gate to cover the union of data gates 1 and 2. Echoes also should not be allowed to clip during scan. |

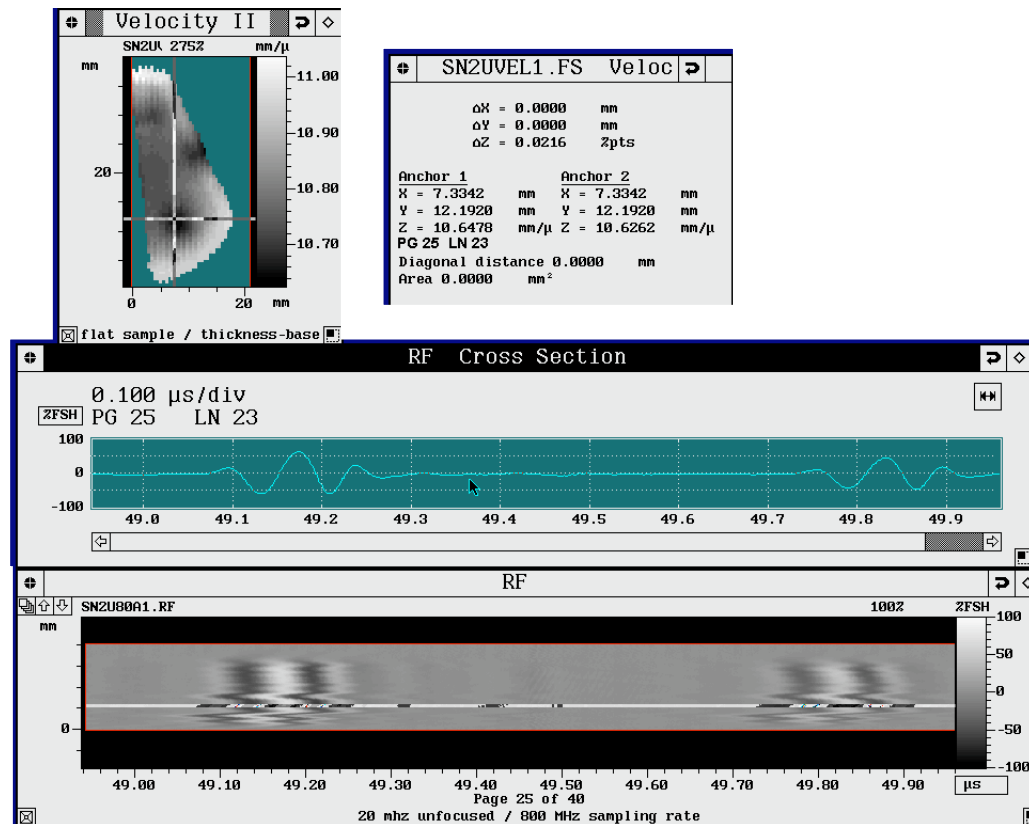| |
|---|
| Perform Full B-scan. It is recommended that step size equals scan increment established in c-scan setup. Save parameter and RF B-scan files. |

A-11

A-12

Turn Front Surface follower gate off. Set data gate 3 on first reflector echo. Set RF B-scan gate on first reflector echo.

Perform Full B-scan. Save parameter and RF B-scan files.

Remove sample from the supports. Set data gate 4 on first reflector echo. Set RF B-scan gate on first reflector echo.

Perform Full B-scan. Save parameter and RF B-scan files.

Click on the B-scan image windows to examine phase relationships of B1 compared to B2, and first reflector echo with sample present compared to that without sample present at several scan locations.

Obtain water temperature/sonic velocity in water.

Close B-scan image windows corresponding to reflector plate echoes.

Click on B-scan image window corresponding to B1,B2 echoes.

Select "Velocity/Thickness" under Process menu. Select Feature = Velocity and TOF detection method = Correlation on pop-up menu. Fill in rest of required information in pop-up menu and then click on "GO" to form image.

Perform Image Post-processing as needed.

Operating Procedures:

A. Scan Setup and Data Collection. (Note that the procedures outlined here discuss using 2 successive back surface echoes [B1 and B2]; it is possible to use the first front surface (FS) and first back surface (B1) echoes as the two needed echoes if the material and experimental conditions do not allow a second back surface echo (B2) of sufficient amplitude. If it is needed to use FS and B1, substitute FS for B1 and B1 for B2 in the procedures below.)
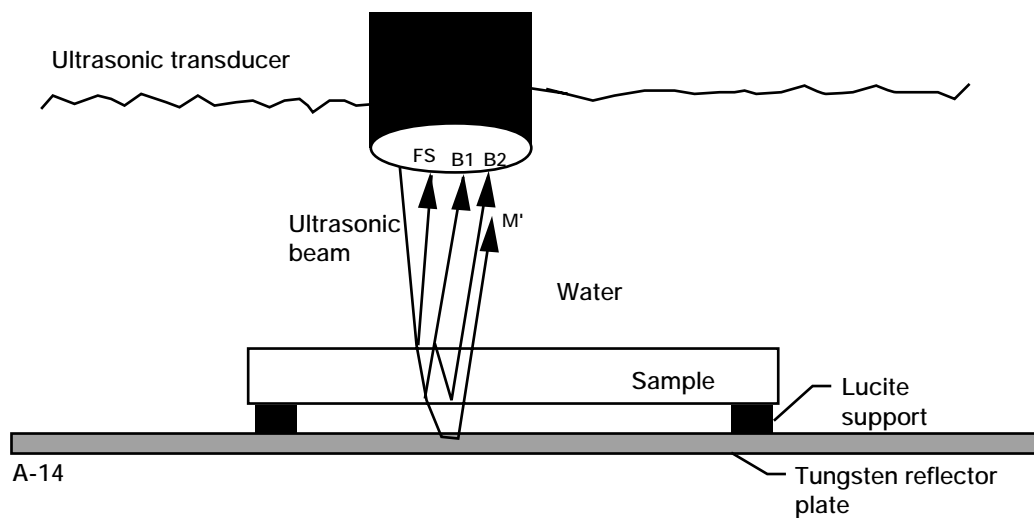
NOTE: All 3 RF B-scans should be done consecutively, on the same day, to avoid any effects of water temperature fluctuations.

(1) See fig. A14. Place the reflector plate in the immersion tank. The recommended material for the reflector plate is 0.159 cm (1/16 in.) - 0.3175 cm (1/8 in.) or thicker flat tungsten plate due to the large acoustic impedance mismatch between tungsten and water. A tungsten reflector plate results in the highest possible reflection amplitude for the echo reflecting off of the reflector plate.

(2) Place at least 2 supports on the reflector plate so that the sample to be scanned can be placed on these supports without the supports interfering with the wave propagation (to the greatest extent possible). It is important for the cubes to have the same height/thickness so that the sample is as level as possible. 1.27 by 1.27 by 1.27 cm (1/2 in.) cubes cut from 1.27 cm thick Lucite sheet work well because Lucite sheet can be found that is very uniformly thick. An alternate procedure would be to suspend the sample over the reflector plate, or have the reflector plate positioned vertically with the sample positioned parallel to it. However, in the latter procedures, it may be more difficult to level the sample or make the sample parallel to the reflector plate compared to the initial procedure given.

A-13

Ultrasonic transducer

FS   B1 B2

M'

Ultrasonic
beam

Water

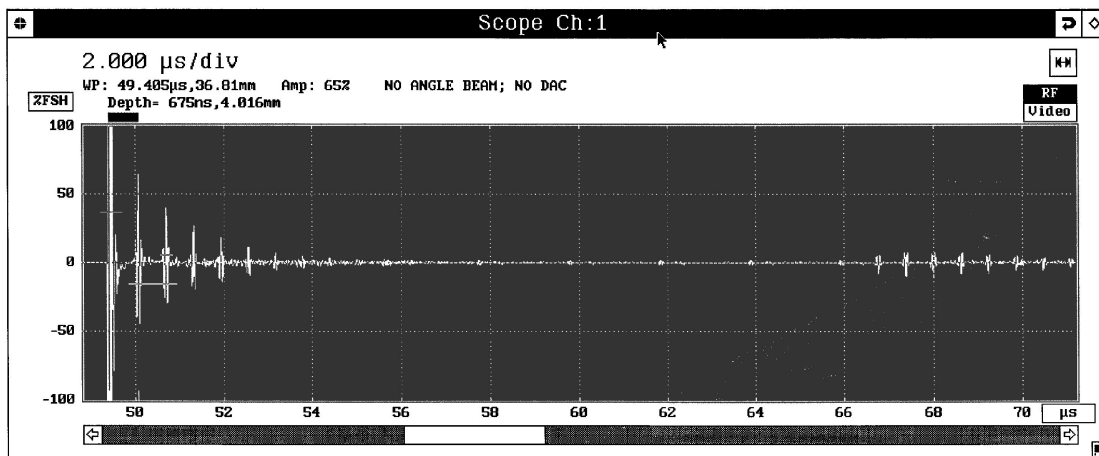Sample

Lucite
support

A-14

Tungsten reflector
plate

(3) Place the sample on the supports and position the transducer over the center of the sample so that the first set of *sample* echoes (first front surface echo and at least 2 successive back-surface echoes), and the first echo off the reflector plate are seen in the digital oscilloscope display (fig. A15). The transducer should be positioned above the sample at distances determined initially by the focal distance. (If an unfocused transducer is being used, ref. A1 has a list of recommended ranges of transducer-to-sample distances based on transducer element size and frequency. A good initial starting height is approximately 2.54 cm (1 in.) - 5.08 cm (2 in.) for most unfocused transducers.) The reflector plate echo may be low in amplitude compared to the back surface echoes so that pulser-receiver gain/ attenuation settings, or Sonix A/D board gain settings may have to be increased to see this echo. IT IS CRITICAL TO HAVE SETUP SUCH THAT REFLECTOR ECHOES WILL NOT INTERFERE WITH THE SECOND SET OF SAMPLE ECHOES BECAUSE THE SECOND SCAN OF THIS PROCEDURE REQUIRES GATING THE REFLECTOR ECHO. DO NOT CONFUSE THE ECHOES OFF THE REFLECTOR PLATE WITH THE SECOND SET OF SAMPLE ECHOES. The second set of sample echoes will always occur at twice the delay time where the first set of sample echoes occurs. A way to note the reflector plate echo is to raise and lower the sample by hand while noting the time location of the stationary echo corresponding to the stationary reflector plate. In an experimental setup used by the authors with a 3 mm thick sample of ceramic material placed on 1.27 cm lucite supports sitting on a tungsten reflector plate, the first set of *sample* echoes began at ~49 µsec on the digital oscilloscope, and the first *reflector* echo occurred at ~67 µsec (fig. A15). The second set of *sample* echoes began at ~98 µsec thus not interfering with the reflector echoes. After satisfactory reflector echo is obtained, establish scan start (choice under scan menu).

(4) Set the c-scan setup appropriately for the desired scan area and resolution. It is recommended that the scans be run with an increment of ≥0.5 mm so that the size of the scan (remember, the echoes are being digitized and stored) and the time of the scan are reasonable. SET A/D SAMPLING RATE TO 800 MHz and keep at this rate for entire procedure. More desirable would be to have the Sonix 81G 1 GHz A/D board so that ETS sampling is not needed. Lower sampling rates than 800 MHz will provide representative but coarse images. It is recommended to scan at scanner velocity and acceleration settings that minimize waveform jitter due to manipulator bridge vibration.

(5) Turn the Front Surface Follower Gate (FSFG) ON and set it on the front surface echo of the sample appro- priately as done for c-scans (remember the threshold sensitive nature of the FSFG). Focus attention on the 2 successive back surface echoes (B1, B2). Try to make B1 and B2 echo amplitudes about 30 to 80 percent of the oscilloscope display height by adjusting pulser-receiver attenuation/gain and/or Sonix A/D gain. Turn data gates 1 and 2 on, and hit "home" to have gates show up on scope. Set data gates 1 and 2 individually over the successive back surface echoes with data gate 1 on the earlier back surface echo. DATA GATES 1 AND 2 ARE THRESHOLD SENSITIVE WHICH MEANS THAT THE HEIGHT OF THE DATA GATE MUST BE SET SO THAT THE ECHO PEAK EXCEEDS THE GATE HEIGHT FOR THE SCAN OVER THE SAMPLE (but not for the scan over outlying areas surrounding sample as for example outlying areas surrounding a circular disk within a square area scan). The threshold sensitive feature is included to distinguish background from valid sample data. This can be accomplished by initially running the transducer over the scan area while viewing the echo heights. IT IS IMPORTANT NOT TO HAVE ECHOES CLIP DURING SCAN. The gates must also cover the extent of the echoes (don't be chintzy here!). Turn on the RF B-scan gate and set it to cover the union of data gates 1 and 2. The RF B-scan data gate is NOT threshold sensitive. Hit "Follows = Yes" for B-scan gate.

(6) Perform Full B-scan (choice under Scan Menu). In order to have the rf b-scan step size equal to the scan increment specified in c-scan setup, set RF b-scan "steps (frames)" equal to the "step data points + 1" specified during your c-scan setup (procedure A2). (For your information, only the RF gate will move during the B-scan while the data gates will remain stationary although they maintain their respective positions with regard to the RF gate.) After the scan, return to scan start. Do not change setup (gate positions, lengths, and thresholds) before saving the parameter and image files. Save parameter and image files.

(7) Leave the sample in place. TURN FSFG OFF. Focus attention now on first echo off the reflector plate. Adjust pulser-receiver attenuation/gain and/or Sonix A/D gain so that echo amplitude is about 30 to 80 percent of the oscilloscope display height. If this echo is too noisy, reduce gain to satisfactory level so that echo is at least 10 to 20 percent of oscilloscope display height. IT IS IMPORTANT NOT TO HAVE ECHO CLIP DURING SCAN. Turn data gate 3 on and hit "home" to have gate show up on scope. Set data gate 3 over the first echo from the reflector plate. DATA GATE 3 IS THRESHOLD SENSITIVE. Make sure the gate covers the extent of the echo. Turn on the RF B-scan gate and set it over data gate 3, and to the same length as data gate 3. Perform Full B-scan (choice under Scan Menu) leaving scan settings the same as for the prior scan. After the scan, return to scan start. Do not change setup before saving the parameter and image files. Save parameter and image files.

A-15
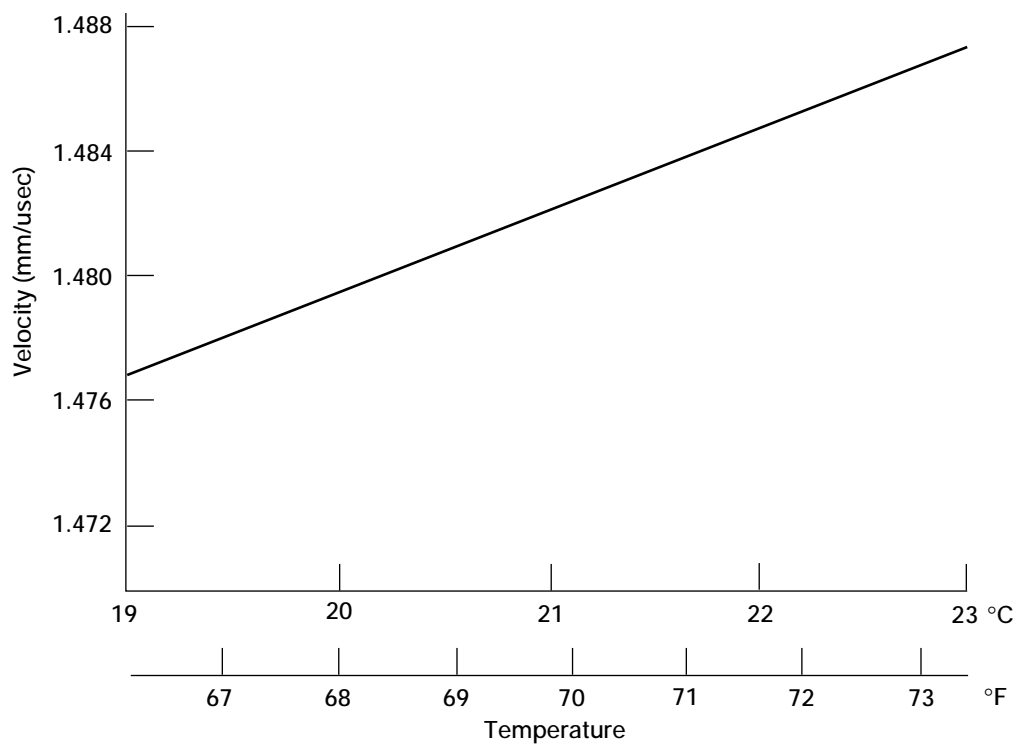
Appendix 16.—Velocity of water vs. temperature from ref. A2.

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(8) Remove the sample from the supports. Focus attention now on the first echo of the reflector plate which will have moved slightly in time (1 to 5 μsec) and will have increased significantly in amplitude. Adjust pulser-receiver attenuation/gain and/or Sonix A/D gain so that echo amplitude is about 30 to 80 percent of the oscilloscope display height. IT IS IMPORTANT NOT TO HAVE ECHO CLIP DURING SCAN. Turn data gate 4 on and hit "home" to have gate show up on scope. Set data gate 4 over the first echo from the reflector plate. DATA GATE 4 IS THRESHOLD SENSITIVE. Make sure the gate covers the extent of the echo. Turn on the RF B-scan gate and set it over data gate 4, and to the same length as data gate 4. Perform Full B-scan (choice under Scan Menu) leaving scan settings the same as for the prior scan. After the scan, return to scan start. Do not change setup before saving the parameter and image files. Save parameter and image files.

(9) Examine phase relationships of (a) B1 compared to B2 and (b) reflector echo w/sample present compared to that without sample present. at several scan locations. Because the phase relationship between the echoes is likely to be the same at scan locations throughout the sample unless significantly different material properties are encountered, it is felt that examination of the phase relationships at several locations is valid to make a decision for the whole sample. These phase relationships are important for the computation of the velocity image. The phase relationships can be determined by performing "cross-section" under "Visualize" menu on the respective RF B-scan images. Find a page and line of the respective RF b-scan images where the echoes show up well on the RF B-scan cross-section oscilloscope. This examination will allow you to note whether the echoes are the same polarity or phase-inverted with respect to each other. The examination must be done extremely carefully. Note the relationships.

(10) Take the water temperature. Using the provided Water velocity vs. Temperature graph (fig. A16), obtain the water velocity. If the scan is being performed in a fluid other than water, or the user wants to determine a more precise water velocity, the velocity of ultrasound in the fluid can be determined by recording the times (T) where ultrasonic peaks occur for 2 Z positions of the transducer. Velocity will then be determined from $V = (Z1 - Z2)/(T1 - T2)$.
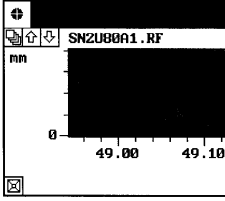
B. Velocity Image Formation

(1) Under File menu, load RF B-scan image and parameter file corresponding to the back surface echoes obtained (first scan performed) in Reflector Plate velocity imaging data acquisition procedure (procedure A6).

(2) Click on the B-scan image window. Under Process menu, select "Velocity/Thickness." A Velocity/Thickness window will pop-up for user input (fig. A17). To begin user input, click on the "File" buttons which will open up a directory window where RF B-scan images are stored. In the appropriate locations, specify the B-scan images corresponding to the first reflector plate echo with and without the sample present. Select Feature = Velocity and TOF detection method = Correlation. Specify ABS, Same Polarity, or Phase Inv for B1,B2 echoes phase relatio-nship. Ditto for reflector plate (with and without sample present) phase relationship. Select Image Range = Full. (No bounds can be entered for an image where the Full Range is displayed.) Input the immersion fluid velocity and associated error in the couplant velocity entry and error input boxes, respectively. Click on GO to begin image formation. A "% complete" status line will be displayed so that the user can track progress of image formation.

C. Velocity Image Post-processing

(1) After image formation is complete, analyze the image using "Show Hist" under Process menu. Histogram display shows bars in gray scale values corresponding to gray values in image. If it is desired to see the histogram bars in white, open the palette window and select S8 default color scheme. Adjust the lower hinge on the color bar to 100 percent using the slide bar at the bottom of the box. The histogram is useful for examining the range of output values. If the histogram contains stray values that are significantly outside the main distribution of values, it is likely that setting new, tighter bounds that filter out stray values and performing a revised image formation (performing step B4) with these bounds will significantly increase the resolution of inhomogeneity.

(2) The following step should be used only to flag/filter extreme high and/or low values. After examining the histogram, if it is desired to flag extreme high and/or low values, use the mouse to drag the palette hinge points at each end of the histogram display to the desired locations such that new bounds are defined. Record the minimum and maxi/mum seen at the top of the histogram display, or move the histogram display to an unimpeded position so

VELOCITY/THICKNESS ANALYSIS

B-Scan Images for Reflector Plate

Sample Present: [File] SN2U80B1.RF

Sample Removed: [File] SN2U80C1.RF

Feature: [Velocity]   [Thickness]

TOF Detect: [Peak-to-peak] [Correlation]

Echoes: [Abs]   Echo 2:   [Abs]
            [Same Pol]   [Pos]
            [Phase_Inv]   [Neg]

Plates: [Abs]   Plate 2: [Abs]
            [Same Pol]   [Pos]
            [Phase_Inv]   [Neg]

Image Range: [Full] [Exp ± Tol] [Bounded]
    Expected: mm/µs
    Tolerance: mm/µs
    Extreme Values: [Filter]

Background: [Color] [Black] [White]
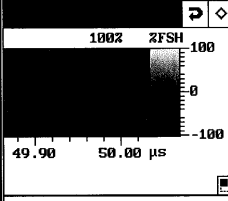
Couplant Velocity: 1.48   mm/µs
Coupl Vel Error (Optl): 0.005   mm/µs

[Go]   [Cancel]   [OK]

SN2U80A1.RF
mm

0

49.00   49.10

100%   %FSH
                        100
                        0
                        -100
49.90   50.00 µs

A-17

that these values will show up after "Velocity/Thickness" is reselected from the Process Menu. Repeat step B2 with the following modifications: Image range = bounded and enter the minimum and maximum bounds just discussed. The user can also use: Image range = Exp +/- Tol option which represents "Expected value plus or minus a tolerance." For the latter, the user is to enter an expected value for the constant and a tolerance value. For either option, if it is desired to FILTER out-of-bounds (flagged) values, set Filter = on. When Filter = on, flagged pixels are replaced by the gray scale average of its 8 nearest unflagged neighbors if in the interior of the image or its 3 or 5 nearest unflagged neighbors if on the border of the image. With Filter = off, flagged pixels will be demarcated red (above upper bound) and blue (above lower bound). From an experimenter's point of view, it is advisable NOT to turn filter ON until results of bounded analysis (with filter OFF) can be investigated. Repeat this step as necessary.

(3) If it is desired to have a black or white background for the image, repeat step B2 with Background = Black or White. Note that a histogram of values is no longer valid because the background is now included in the histogram calculation.

(4) After desired image is obtained, select "Duplicate Image" under File menu. Select "Smooth" under the process menu to interpolate the image results and provide a smoother-appearing image. Save *.VS image(s). Do not overwrite image comments concerning velocity statistics.

(5) If it is desired to view individual velocity values in the full-processed or bounded velocity image, select "Locate/Measure" under the Measure menu and move white bar cursor (using mouse cursor w/left mouse cursor depressed) in the image to desired scan location. Click on left mouse button to bring up Feature Window which will show x,y (mm) location and velocity value (z) in mm/µsec corresponding to that scan point where cursor is located. Move cursor over the image to view velocity values at all locations desired. Note that cursor placed over background or scan locations where out-of-bounds velocity values occurred (procedure C2) will report invalid values and these are to be ignored.

(6) If it is desired to view a plot of the velocity values at a particular image line, select "cross-section" under visualize menu and move white cursor bar across image by moving mouse w/left mouse button depressed. The cross-section bar orientation is toggled by depressing the left and middle mouse buttons simultaneously.

(7) If it is desired to view the raw waveform data corresponding to a particular scan location, select "Locate/ Measure" under the Measure menu and move white bar cursor (using mouse cursor) in originally-formed velocity (not duplicate) image to desired scan location. Click on left mouse button to bring up Feature Window which will show x,y location and velocity value (z) in mm/µsec corresponding to that scan point where cursor is located. Below this inform-ation in the Feature Window is the page (PG) and line (LN) numbers that essentially give the scan coordinates. Click on RF image of interest (3 images are available corresponding to the 3 scans run). Make sure RF image is at 100 percent magnification. Select "cross-section" under Visualize menu. This will cause RF cross-section (scope) window to pop-up. Move the mouse to RF image and select the PG desired using up/down arrows in RF image window. To select the desired LN number, move heavy white cursor (via mouse cursor w/left mouse cursor depressed) within RF image PG to the LN desired. View the RF cross-section for the raw waveform data corresponding to the PG and LN numbers (scan location) selected. To repeat procedure, start at beginning of this paragraph.

APPENDIX REFERENCES

A1. Ultrasonic Transducers for nondestructive testing. Part no. P391. Panametrics, 221 Crescent Street, Waltham, MA 01254 (800-225-8330).
A2. Nondestructive Testing Handbook, second edition, Volume 7 Ultrasonic Testing, eds. Birks, A.S., Green, R.E., and McIntire, P. American Society For Nondestructive Testing, 1991, p. 225.

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13. ABSTRACT *(Maximum 200 words)*

This article describes the commercial implementation of ultrasonic velocity imaging methods developed and refined at NASA Lewis Research Center on the Sonix c-scan inspection system. Two velocity imaging methods were implemented: thickness-based and non-thickness-based reflector plate methods. The article demonstrates capabilities of the commercial implementation and gives the detailed operating procedures required for Sonix customers to achieve optimum velocity imaging results. This commercial implementation of velocity imaging provides a 100x speed increase in scanning and processing over the lab-based methods developed at LeRC. The significance of this cooperative effort is that the aerospace and other materials development-intensive industries which use extensive ultrasonic inspection for process control and failure analysis will now have an alternative, highly accurate imaging method commercially available.

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